PERFORMANCE OF STATE ESTIMATORS INCORPORATING VOLTAGE AND CURRENT PHASORS FROM PMU

BY

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Dedicated to my beloved father Haji Ahmad Sayal (Late), to my beloved mother who always supported me in achieving my milestones and my siblings

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LIST OF ABBREVIATIONS

PSSE	:	Power System State Estimation
WLS	:	Weighted Least Square
WLAV	:	Weighted Least Absolute Value
LMR	:	Least Measurement Rejected
PMU	:	Phasor Measurement Units
SCADA	:	Supervisory Control and Data Acquisition
EMS	:	Energy Management System
ISO	:	Independent System Operator
CEE	:	Cumulative Estimated Error
AOR	:	Ability of Rejection Bad-Data
RTU	:	Remote Terminal Unit

ABSTRACT

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Power System State Estimation (PSSE) is considered to be the back bone of modern electric power system. It is used by almost all the Energy Management Systems (EMS) in the world to ensure the security of the system. State Estimation (SE) ensures the real-time monitoring and control of power systems. Phasor Measurement Unit (PMU) is the most popular meter in the modern power systems because of its high accuracy but are very limitedly used because of its high installation cost. Every PMU meter reading has Global Positioning System (GPS) time stamp and hence very accurate when compared to conventional Supervisory Control and Data Acquisition (SCADA) meters. Consequently, the use of PMU meters along with SCADA can improve the performance of the PSSE irrespective of the estimator used. Weighted Least Square (WLS) estimator is most commonly used for the estimation purpose but it carries the drawback of non-robustness which fails when subjected to a Bad-Data. In this thesis, phasor measurements (voltage and current phasors) are incorporated into three SE algorithms: Weighted Least Square (WLS), Weighted Least Absolute Value (WLAV) and Least Measurement Rejected (LMR). This will allow to simulate the PMU meter readings for estimation purpose and will improve the estimation performance. Estimator algorithms are modified so that they can work with mixed measurement system: power flows, power injections, voltage magnitudes from

SCADA meters and phasor measurements from PMU meters. The phasor measurements have been included into Jacobian matrix of each algorithm. In this thesis, the LMR estimator has been further modified to have better performance than other estimators. The tolerance parameter of LMR estimator has been investigated and modified to get good estimation results with and without PMU inclusion. Moreover, the performance of LMR estimator has been investigated under different Bad-Data scenarios which proves the robustness of LMR estimator. The thesis also investigated the importance of locating PMU meters in a power system. Two PMU have been placed heuristically into the system. One PMU is fixed at reference bus while another PMU is located at different buses heuristically. The placement of PMU must be chosen very carefully so that the best performance of the estimation process is achieved. IEEE-14, IEEE-30 and IEEE-118 bus systems have been used for performance evaluation of the modified LMR estimator in the presence of single, multiple non-interacting and multiple interacting Bad-Data.

ملخص الرسالة

الاسم الكامل:[فرحان عمار احمد]

عنوان الرسالة:[أداء مقدر حالة نظام الطاقة الكهربائية عند دمج طوري الجهد و التيار الكهربائيين من وحدات قياس الطور]

التخصص:[الهندسة الكهربائية]

تاريخ الدرجة العلمية:[ديسمبر 2016]

يعتبر تقدير حالة النظام (PSSE) العمود الفقري لأنظمة القوى الكهربائية الحديثة، و يستخدم في أغلب أنظمة إدارة الطاقة الكهربائية (EMS) في العالم للتحقق من أمن النظام. يُحقق تقدير الحالة (SE) مراقبة الوقت الحقيقي و التحكم في أنظمة الطاقة. تُعد وحدة قياس الطور (PMU) من أكثر الأجهزة شيوعاً في أنظمة الطاقة الحديثة نظراً لدقتها العالية لكنها محدودةٌ بسبب ارتفاع تكلفتها. كل وحدة قياس طور مرتبطة بنظام تحديد المواقع العالمي (GPS) مما يعزز من دقة قياساتها مقارنةً بقياسات نظام التحكم الإشرافي و تجميع البيانات التقليدي (إسكادا SCADA). لذلك، فإن استخدام وحدات قياس الطور مع نظام إسكادا سيحسن أداء مُقدّر حالة نظام الطاقة بغض النظر عن المُقدّر المستخدم. يُستخدم مُقدّر المربعات الصغرى الموزونة (WLS) في أغلب الأنظمة بهدف تقدير الحالة لكن عيب هذا المُقدّر أنه ليس قوياً إذ يفشل عند تعرضه لبياناتٍ سيئةٍ. في هذه الأطروحة تم دمج قياسات الطور (أطوار الجهد و التيار) في ثلاث خوارزمياتٍ لتقدير حالة النظام، و هي: المربعات الصغرى الموزونة (WLS)، و القيم المطلقة الصغرى الموزونة (WLAV)، و أقل القياسات المرفوضة (LMR). هذا الدمج سيمكننا من محاكاة قياسات وحدات قياس الطور المستخدمة لغرض تقدير الحالة و سيحسن من أداء التقدير. تم تعديل خوارزميات المُقدّر بحيث تتمكن من التعامل مع نظام قياساتٍ مختلطةٍ يشمل: الطاقات المتدفقة، و الطاقات المحقونة، و مقادير الجهد الكهربائي من وحدات إسكادا، بالإضافة إلى قياسات الطور من وحدات قياس الطور. تمت إضافة قياسات الطور في المصفوفة الجاكوبية لكل خوارزمية. في هذه الأطروحة، تم إجراء مزيدٍ من التعديل على مُقدّر LMR ليعطي أداءً أفضل من بقية المُقدّرات؛ إذ تم بحث ضبط معامل التفاوت الخاص بمُقدّر LMR و تعديله ليعطي نتائج تقديرٍ جيدةً سواءً أضفنا وحدات قياس الطور أم لم نضفها. علاوةً على ذلك، تم تقييم أداء مُقدّر LMR في ظل وجود سيناريوهاتٍ مختلفةٍ من البيانات السيئة، ما أثبت قوة مُقدّر LMR. كما بحثت الأطروحة أهمية توزيع وحدات قياس الطور على نظام الطاقة الكهربائي. قمنا بتوزيع

اثنتين من وحدات قياس الطور توزيعاً تجريبياً؛ حيث ثبتنا واحدةً من الوحدات عند عقدةٍ كهربائيةٍ مرجعيةٍ و وزعنا الوحدة الأخرى توزيعاً تجريبياً على عددٍ من العقد الكهربائية الأخرى. يجب مراعاة توزيع وحدات قياس الطور بعنايةٍ للحصول على أفضل أداءٍ لعملية التقدير. تم اختبار فعالية الخوارزمية المعدلة من LMR على ثلاث أنظمة اختبار من أنظمة معهد مهندسي الكهرباء و الإلكترونيات (IEEE) و هي: IEEE-14، IEEE-30، و IEEE-118، بوجود أنواعٍ مختلفةٍ من البيانات السيئة سواء كانت مفردةً، أو متعددةً غير متفاعلةٍ، أو متعددةً و متفاعلةً مع بعضها البعض.

CHAPTER 1

INTRODUCTION

1.1 Importance of State Estimation

The idea of Power System State Estimation (PSSE) was developed and introduced by Fred Schweppes in 1968. According to Fred's research, a state estimator is an algorithm to process raw and redundant conventional meter readings and other information like network topology, circuit breaker status in order to estimates the state of the system [1][2][3]. State Estimation (SE) is the back bone of today's modern electric power system security and it is used by almost every Energy Management System (EMS) in the world. SE is one of the basic tool to ensure that system is running in secure mode while meeting all its constraints. It helps in building complete picture of a power system which is used by Independent System Operator (ISO) for different application: like monitor system security, assessment, control, economic dispatch, ancillary services, and spinning reserve etc. Traditional SE has been going through essential development due to innovation of Phasor Measurement Units (PMU). Utilities process the measurements from different sensors to estimate the operating condition of the system. The measurements which are wrongly recorded because of the large noise, calibration issue or telemetering are called Bad-Data [4]. Bad-Data affects the estimation process and results in wrong estimation of the system states. Outlier is another term used for measurement which lies away from the expected limit. Bad-Data can be mainly classified into two categories; Single Bad-Data and Multiple Bad-Data [5]. Multiple Bad-Data mostly occurs in very large systems. Multiple Bad-Data can be strongly correlated to each other and this correlation will be having a huge impact on estimation results. The accuracy of PSSE can be improved by incorporation of a PMU. PMU has increased its importance in PSSE because of the new its features when compared with conventional SCADA measurement system. The conventional power flows and power injections are nonlinear functions for estimating system states while PMU offers synchronized phasor measurements which results in linear models for PSSE. The accuracy of phasor measurements is very high in comparison with conventional SCADA measurements [6]. It is possible to increase the accuracy of SE by optimally placing PMUs in the power system and combining both conventional measurements and PMU phasor measurements [7].

Hybrid State Estimation is conducted by incorporating both SCADA measurements as well as PMU phasor measurements and this has helped in enhancing the accuracy of the estimation process. Phasor measurements can be used to increase the redundancy and synchronization as well as the accuracy of the system [8]. In this thesis, both voltage and current phasors have been included into existing state estimator algorithms; Weighted Least Square (WLS), Weighted Least Absolute Value (WLAV) and Least Measurement Rejected (LMR). In this thesis, the phasor measurements have been included into Jacobian matrix of each estimator to enhance the performance of the estimation process in the presence of single, multiple non-interacting and multiple interacting Bad-Data and this approach has successfully improved the estimation accuracy. In this thesis, IEEE 14, IEEE

30 and IEEE 118 bus systems have been used to evaluate the performance of the proposed approach which is to incorporate voltage and current phasors into existing state estimators.

1.2 Motivation

Synchro phasors are meters that ensure highest level of estimation accuracy as well as very fast refreshing data rate. Whenever it is installed in a substation, it can measure voltage and current phasors of all incoming and outgoing lines based on the availability of the required facility and channel limit of PMU [9][10]. In order to use these accurate readings in the state estimators, the algorithms need to be modified accordingly so that it can handle the phasor measurements. Inclusion of phasor measurement results the highest level of accuracy with less computational speed and higher robustness [11].

SE is performed mainly by conventional SCADA meter measurements which are affected by white noises and these measurements are not much preferred in terms of accuracy when compared with PMU phasor measurements. Consequently, lot of research is going on for the inclusion of PMU phasor measurements to improve the accuracy of state estimators. However, there are many practical challenges to incorporate PMUs into the existing state estimators. Another challenge is the selection of the locations, where the PMU should be placed in the power system because of high cost of installation of PMU.

Research is going on to improve the estimation accuracy by different approaches and algorithms specially when the system is subjected to Bad-Data. In this thesis, the motivation to improve the SE accuracy in the presence of Bad-Data (single or multiple) has been carried out by incorporating the phasor measurements from PMUs. The LMR estimator is used and modified accordingly to make it capable of dealing with the phasor measurements of PMUs. Tolerance parameter to reject large errors in measurements is chosen properly while operating with LMR estimator. The performance of LMR estimator has been evaluated in the presence of Bad-Data and compared with other two well established estimators; WLS and WLAV. Placement of a PMU in the power system is carried out in heuristic approach to further improve estimation accuracy.

1.3 Objectives

In this thesis, it is intended to improve the state tracking accuracy of state estimators in the presence of different Bad-Data scenarios. Robust estimator plays a key role in PSSE. Various estimators are proposed to improve the efficiency in detecting different types of Bad-Data. In order to improve the performance accuracy of SE, voltage and current phasors are simulated in the existing estimator algorithms. This will allow the incorporation of PMUs. LMR estimator has been further modified to have more robust estimator that can handle the presence of Bad-Data. The tolerance of LMR estimator has been chosen carefully. The appropriate tolerance value has been achieved iteratively for meters which ensures the rejection of unreliable measurements to deliver better performance of the estimation process. The final approach of achieving the objective is the proper selection of the PMUs locations in order to ensure best performance of the estimation process. This thesis addresses this issue with care and proposed such locations of PMUs installation for different sizes of test cases.

1.4 Contribution

This thesis has three main contributions. Firstly, the phasor measurements of voltage and current have been incorporated into the existing Jacobian matrix of LMR estimator. This contribution made the LMR estimator capable of working with the PMU readings along with the conventional SCADA meter measurements. The inclusion of PMU readings in the measurement series has improved the accuracy of estimator which can be noticed in section 5.2 to 5.4. Secondly, the LMR estimator has been presented with proper selection of the tolerance values. The tolerance parameter of LMR estimator is an important control parameter which actually helps in rejection of unreliable measurements during the estimation process. Each of the meter readings should be provided with an appropriate tolerance value which will help the estimator to reject the unreliable and ensures the higher efficiency of the estimation results. In this thesis, the tuning parameter is selected iteratively and proposed a way of selecting tolerance properly when the reading comes from PMU meter. Thirdly, the important aspect of PMU placement has been investigated in the thesis. PMU is installed in the existing power system in such a way that it provides best state estimation results. The placement has been carried out heuristically. The proposed approach with all its important aspects to improve the accuracy of state estimators has been successfully implemented and tested on IEEE 14, 30 and 118 bus systems.

1.5 Thesis Structure

The thesis is organized as follows: Chapter 2 covers the details and literature review about PSSE and all its important aspects like observability, redundancy level, critical measurements, critical sets and multiple interacting measurements. Chapter 3 explains the numerical steps to calculate important aspects of SE. Chapter 4 covers the method to incorporate both voltage and current phasors, as well as mathematical formulation of modified state estimators with inclusion of phasors. It also includes the modification of LMR estimator with iterative selection of tolerance parameter. Furthermore, it explains the heuristic procedure to place PMU meters into the system. In chapter 5, the measurement simulation procedure and SE results are discussed in detail with tables and figures. The conclusions and future works are presented in chapter 6.

CHAPTER 2

POWER SYSTEM STATE ESTIMATION

2.1 State Estimation Algorithms

Estimators provide reliable database by fitting the raw measurements from system to a mathematical model for monitoring, security assessment and control functions. In literature, several researchers have attempted on different SE techniques while considering number of practical challenges and difficulties.

The idea of PSSE was developed and introduced by Fred Schweppes in 1968. According to Fred's research, a SE is an estimation algorithm that process raw and redundant conventional SCADA meter readings and other information about electric power system to estimates the state of the system [1][2][3]. The static-state estimation is the combination of two fields; load flow study and statistical estimation theory.

A basis graphical overview of SE processes is shown in Figure 2.1. First, there is a network topology processor which helps in identifying and verifying power system network parameters such as transmission line data, switches, circuit breakers status etc. Then network observability analysis is carried out to check if there are sufficient number of measurements available to conduct SE. The observability check can be verified by null space or rank of Jacobian matrix [12]. If the power system network under investigation is not observable, then there is need for some pseudo-measurements. These measurements are less accurate and are based on historical data or the dispatcher's objective guess [13].

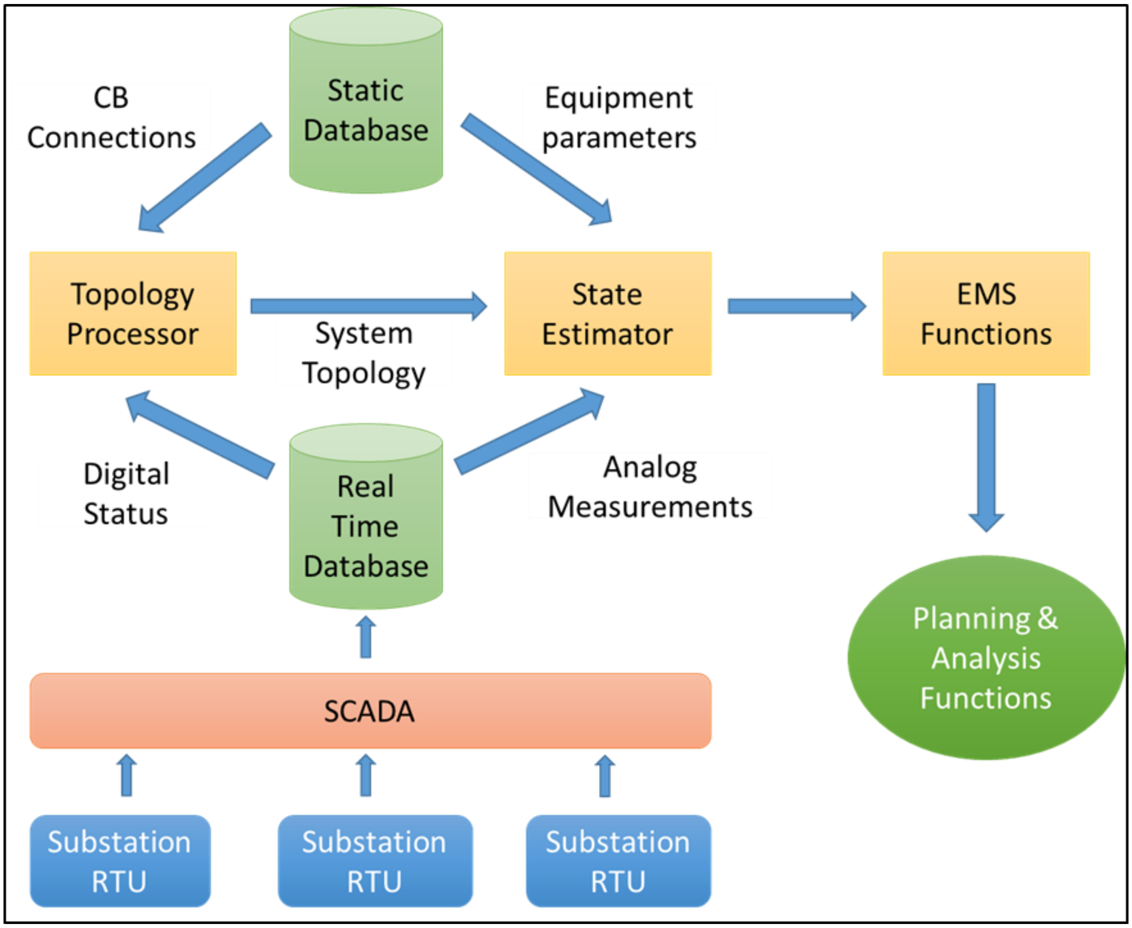

Figure 2.1 Power System State Estimation

An estimator uses all this data provided to get a unique solution. At last, the presence of Bad-Data is detected and those bad measurements with a gross error or high noise are removed to provide an accurate and reliable estimation solution [14]. Bad-Data can be filtered out during or after the estimation process. It depends upon the feature of state estimator which is processing data for the estimation process.

There are alternative approaches in the estimation process which have been proposed like Orthogonal Factorization, Hybrid Method and Augmented Matrix Approach [15]. Kalman filtering based power system state estimator has been proposed in which load variation have been considered in each sample [16].

PSSE has three main functions to perform; observability analysis, SE, and Bad-Data analysis and filtering. SE involves computational procedure to optimize an objective function and the objective function can be of first order or second order. WLS is a conventional state estimator which is commonly solved by newton iterations and state estimator like WLAV which is based on linear programming method [17]. The system state variables are computed either statically or dynamically. The above mention methods are for static SE [16]. There are also heuristic techniques to find the state of a system. In dynamic SE, the system states are continuously computed and monitored at regular time intervals. There are many methods like Kalman filter, invariant imbedding, nonlinear observer technique and Leapfrog algorithm which are used in dynamic SE [18][15].

WLS estimator can be quickly solved with triangular factorization method because the gain matrix G has sparsity. This method is also called Normal Equation method [19]. WLS estimator can also be solved by orthogonal transformation method and if these two methods are combined then it will be called a hybrid method [20]. But Normal Equation method fails if Jacobian matrix H is ill conditioned or if the sparsity is affected [21]. In this method, numerical instability leads to ill conditioning and this can be because of the position of reference slack bus, line reactance is negative or there is inappropriate choice of measurements for SE [22]. The Newton method is one of the solution to ill conditioning because it includes the second order gradient of measurements function which are neglected by actual WLS estimator and Newton method is efficient in gradient convergence technique [23].

WLAV estimator has proved itself as a robust estimator in comparison with WLS estimator but it is shown to be susceptible to leverage points for a certain measurements configuration or system [24]. There are post SE techniques that has been proposed in literature [25]. WLAV estimator has a drawback, which is computational burden of algorithm for large power systems. For numerical stability and computational efficiency in linear programming, the scaling has been widely used and it is effective in WLAV estimator as it has been investigated in [26] and it has been shown that the scaling helped in reducing the effect of leverage points. In [27], a robust WLAV-T estimator has been proposed to mitigate the effect of leverage points and it is based on optimal transformation of associated rotation angles and scaling factor in systematic way instead of heuristic way which was proposed in [28]. WLAV estimator also has auxiliary variables which reduce the convergence rate of estimator, so Weighted Linear Least Square (WLLS) was proposed in [29] which had less number of variables than WLAV estimator and its objective function was linear.

PSSE techniques can be divided into two groups; mathematical and intelligence techniques [30]. WLS, WLAV and M-Estimators are among mathematical techniques group. While Fuzzy Interference System, Neural Network based SE, Adaptive Neuron Fuzzy Interference System are among intelligence techniques groups. Mathematical methods are not faster than intelligent techniques but they are more accurate [29].

Several attempts are made for solving PSSE by optimization methods, but SE is a highly nonlinear problem whereas optimization methods go for local minima based approaches. This high nonlinearity leads the optimization method towards several local minima in search space, which provides local solution instead of global one. A local solution will provide huge error between estimated values and actual ones. Convergence of optimization methods is highly dependent on selection of initial values of state variables [17].

A new SE algorithm was proposed that used minimum variance criterion and sequential method for optimal placement of meters in system. Singular Value Decomposition was used for observability analysis and WLS estimator was used for harmonic SE. This method was helpful to minimize the number of meters and there was a noticeable amount of reduction in error while system was full observable. This algorithm was tested on Mazandaran transmission network [31].

2.2 Observability Analysis

The observability can be defined as the capability of an estimator to obtain a unique SE solution with a given data set of certain measurements, network topology, line data, switches and circuit breaker status. Observability is basically dependent on geographical location and total number of different meter measurements in a system. The basic definition and aspects of observability analysis is discussed in [32]. The observability check can be completed using decoupled model under the assumption that meter measurements comes in real and reactive pairs.

2.3 Critical Measurements and Critical Sets

Data redundancy is associated with critical measurement and critical sets. A critical measurement is the one which is associated with system observability and loss of this measurement can be loss of overall system observability. The residual of critical measurement is always zero, so a large gross error in critical measurement is difficult to identify. A critical set consists of two or more redundant measurements but if any of these measurement is removed from the set then the remaining measurement will become critical. The gross error in critical set is also difficult to identify. The identification of critical measurement and critical sets is qualitative problem and it is dependent on location, type, and number of meters in a system [33].

2.4 Measurements Redundancy Level

The performance of PSSE is also dependent on measurement redundancy level of a system. The solution of PSSE is valued if an appropriate number of meter measurements are fed to achieve good data redundancy level. Redundancy is additional measurements, in relation to minimum number of measurements required to make an observable system. The data redundancy in power system can be classified into three levels and the issues related to these levels are also highlighted in this section.

The first level defines the loss of those measurements which will affect the quality of SE, while reliability and overall system observability will be preserved. In second level, the reliability of SE is somehow affected and some of measurements will become critical which were previously redundant. If the redundancy is very low and it is affecting system observability and reliability, then almost all of measurements in this third level will be critical [33].

Measurement redundancy in a power system plays a dominant role for the estimation process. If the redundancy level is good or high, it will not only help in good estimation results but will also be helpful to reduce the effects of Bad-Data into SE.

2.5 Multiple Interacting and Non-Interacting Measurements

The measurements which are strongly correlated will affect the estimated value of each other significantly, if an error is present in one of the measurement. It will cause the good one to appear in error when the other contains a large error. Estimates of measurements with weakly correlated residuals are not significantly affected by errors of other measurements. When measurement residuals are strongly correlated, their errors may or may not be conforming. Conforming errors are those that appear consistent with each other. Multiple Bad-Data may appear in measurements whose residuals are strongly or weakly correlated [34].

2.6 Bad-Data

Bad-Data is a measurement which is recorded with huge error or reverse meter polarity. Surely, this will affect the estimation process on a large scale unless, a robust estimator is used. Some Bad-Data values are obvious and easy to detect like negative voltage magnitudes or a measurement value of several orders small or large when compared with historical data.

The Gaussian assumption of normal distribution for measurement noise becomes wrong when Bad-Data is present into a measurement set. There are two different approaches to handle Bad-Data in PSSE. The first method uses the result of WLS estimator to detect, identify and remove Bad-Data and it is referred to as post processing. The second methodology is to replace WLS estimator by a robust estimator. The robust estimator is less sensitive to small departures from the true measurements. The robustness of state estimator can be affected by meter configuration. For this reason, meter placement in a power system should be in such a manner, so that a certain redundancy level should be achieved, the system should be observable even if there is loss of few measurements and Bad-Data detection capabilities should also improve [35].

If there is a Bad-Data in a meter measurement set, the residual, which is the difference between the measurement and estimated value will be a large value. Chi-Square is one of the famous technique to detect a Bad-Data and it is a statistical approach of hypothesis testing which can be applied to check whether the value of objective function $J(x)$ indicates that the hypothesis is true or not. A more famous and reliable technique is normalized residual method and it has been shown by literature that normalized residual is a reliable method for Bad-Data identification and detection [36].

It has been shown that for a single Bad-Data, the largest normalized residual value corresponds to a bad measurement. This fact has been successfully used to identify Bad-Data by successively removing the measurement with the largest normalized residual. But residual is linear combination of measurements errors and are not capable of identifying multiple interacting Bad-Data specially, Conforming Bad-Data [37]. WLAV is a robust estimator in comparison with WLS, but its estimation solution is suspicious when there are leverage points and these are identified in row vectors of Jacobian matrix. Any measurement whose associated row vector projection is at large distance when compared to others then, it will be a leverage point.

Multiple Bad-Data may be present in a measurement set and it can be strongly or weakly correlated to each other. The strongly correlated measurements with Bad-Data may affect the estimates of each other and a bad value can be estimated from a good measurement. If the measurements are weakly correlated, then an error in one measurement will not significantly affect the estimated values of other meters.

2.7 PMU Inclusion into State Estimation

Inclusion of a line current measurement into the SE helps in enhancing the performance and reliability of the estimation results but there is cost as well for this high quality and reliable estimation process. Measurements pairs help in enhancing the observability and performance of SE and these pairs can be consisting of: 1) a branch with real power flow meter and ampere magnitude meter 2) a branch with reactive power flow meter and ampere flow magnitude meter 3) an ampere magnitude meter with unobservable voltage measurement. The ampere flow measurement offers several advantages like additional information to enhance performance of SE, determination of proper initial condition and the reliability of mix measurement data set can be improved at lower cost [38]. In [25], the author proposed a method for Bad-Data identification for WLS and WLAV, while using ampere measurements as additional to conventional meters. In future, PSSE and most of transmission system monitoring will be carried only by PMU phasor measurements. A lot of research work is going on to make a system observable with only a few number of measurements. Optimal placement of PMU is very crucial in this regard because PMU is very expensive equipment and to swap the conventional SCADA with PMU will require a very huge investment. SE with only phasor measurements is a linear estimation problem [10] and nonlinear estimators are not suitable for SE after investing a large amount of money to install PMU in a system. But current research is still behind to get an optimized and feasible solution to place only PMU in electric power system.

A new Hybrid State Estimation algorithm is proposed to incorporate a limited number of PMU in a system for PSSE problem, so to enhance the state track accuracy and computational speed [11]. Basic idea for Hybrid State Estimation was proposed in [39] and a synchro phasor assisted SE algorithm was presented in [40]. Hybrid State Estimation algorithm proposed in [11] switches between WLS and LAV estimator and this switching is dependent on the available measurements (conventional SCADA or PMU phasor measurement) for the estimation process.

Another WLS based state estimator was proposed which has included both PMU phasor measurements and conventional SCADA measurements [41]. A differential evolution algorithm, which was called Hybrid Taguchi Differential evolution, was proposed [20] to solve estimation problem as optimization problem. This algorithm combines the positive properties of Taguchi Method with differential algorithm to improve accuracy as well as reliability.

Hybrid SE is a reasonable path to follow, until we have both conventional SCADA meters and PMU phasor measurements in power system. Hybrid SE can incorporate both SCADA measurements and PMU phasor measurements and it will help to enhance the state track accuracy and estimation speed. A limited number of PMU can be installed into a system while maintaining system observability, accuracy, and robustness of estimator in the presence of large measurement errors. Phasor measurements can be used to increase redundancy and synchronization as well as accuracy because every phasor measurement has time stamped and very accurate measurement when compared with conventional SCADA.

CHAPTER 3

ASPECTS OF STATE ESTIMATION

3.1 Measurements Simulation

Different types of measurement meters and transformers are used in a power system e.g. ampere meter, voltage magnitude meter, power flow meter, current transformer and potential transformer. Every meter has a certain level of accuracy which needs to be modelled mathematically as random noise in a simulated measurement. This noise can be because of aging of meter, bad calibration, communication error or incomplete metering. This random noise can be induced in a good measurement or actual load flow values using the following equation:

$$z_i = actual_i \left(1 + RND * \sigma_i\right) \tag{3.1}$$

where:

$i = 1, 2 \ldots m$;

$actual_i$ is load flow value of ith meter;

z_i is simulated measurement of ith meter;

σ_i is standard deviation of ith meter;

RND is random number with zero mean and normal distribution varying between (-1 to 1).

There are two stopping criteria for the estimation process; first one limits the number of iteration to a maximum value of 100. Second, the norm must be greater than a certain threshold usually ($1xe^{-4}$) for the next iteration to exist. Different algorithms have different norm indices as stopping criteria.

3.2 Numerical Steps to Identify Critical Measurements and Set

A critical measurement is a non-redundant measurement and its estimated value cannot be affected by other measurements. Therefore, the estimation residual of a critical measurement is always zero, which is the difference between measured and estimated value. Critical measurements are linearly independent in Jacobian matrix and if any ampere magnitude measurement is critical, then it can be implied that the SE solution may not be unique [44]. A measurement z_i will be declared as critical if:

$$r_i = z_i - z\_est_i = 0 \tag{3.2}$$

$$\phi_i = \sqrt{E(i,i)} = 0 \tag{3.3}$$

$$G = H^T R^{-1} H \tag{3.4}$$

$$E = R - HG^{-1}H^T \tag{3.5}$$

where:

r_i is residual and it is the difference between ith measurement z_i and its estimated value z_est_i;

ϕ_i is standard deviation of the ith component of the residual vector;

R is covariance matrix;

$H = \frac{\partial h(x)}{\partial x}$ is known as Jacobian matrix of dimension $(m \; x \; n)$;

m is the number of measurements;

n is number of state variables;

E is residual covariance matrix;

G is known as gain matrix.

As explained in section 2.3, a critical set consists of non-critical measurements but they are strongly correlated. If a measurement set is critical, then the normalized residual of those measurements will be equal and their correlation coefficients ρ_{ij} and φ_{ij} will be having maximum value which can be one. The correlation coefficients are explained in equations 3.6 and 3.7.

$$\rho_{ij} = \frac{R_N(i)}{R_N(j)} = 1 \tag{3.6}$$

$$\varphi_{ij} = \frac{|E(i,j)|}{\sqrt{E(i,i)}\sqrt{E(j,j)}} = 1 \tag{3.7}$$

where:

$R_N(i)$ is normalized residual of ith measurement;

ρ_{ij} and φ_{ij} are the correlation coefficients of $R_N(i)$.

If the values of these factors are equal to 1, then a measurement set will form a critical set but these measurements are not critical measurements and they are still redundant. If any of these measurement from the critical set will be removed, the remaining measurement will become critical now.

A measurement affected by a Bad-Data can be detected and identified only, neither it belongs to a critical pair nor a critical measurement. The normalized residual of measurements belonging to a critical pair will be equal and this makes impossible to identify Bad-Data in a critical pair [34]. For a given data set, n represent the number of buses in the system and H represent the Jacobian matrix. If H is reordered such that number of linearly independent rows are placed at first, such that:

$$H = \begin{bmatrix} H_e \\ H_r \end{bmatrix} \tag{3.8}$$

$$H = \begin{bmatrix} 1 \\ H_r H_e^{-1} \end{bmatrix} H_e \tag{3.9}$$

where:

H_e contains linearly independent rows of Jacobian matrix;

H_r contains the remaining dependent rows.

Now, the sensitivity matrix can be defined as:

$$K = H_r H_e^{-1} \tag{3.10}$$

If any column j in the K matrix has non-zero element at the corresponding ith row, then both of these measurements will form a critical set.

3.3 Identification Approach for Multiple Interacting Measurement

As described in section 2.6, a Bad-Data can be classified into two types: Single Bad-Data and Multiple Bad-Data. While Multiple Bad-Data can be further categorized as Interacting and Non-Interacting. The interaction between two or more measurements can be identified by residual sensitivity matrix *S* and is calculated as:

$$K = HG^{-1}H^{T}R^{-1} \tag{3.11}$$

$$S = I - K \tag{3.12}$$

where:

K is hat matrix;

I is identity matrix;

S is residual sensitivity matrix.

If the value of S_{ij} is larger than the threshold value, then the corresponding measurements will be interacting with each other. In this thesis, the threshold value is 0.1 for the sensitivity matrix. If the measurements are interacting then an error on any measurement will significantly affect the estimated value of the other and it can be identified by normalized residual test, if the error is non-conforming [34].

3.4 Redundancy Level Calculation Method

Measurement meter redundancy level of a power system has a dominant role in SE. If the redundancy level is good or high of the system, it will help to get good estimation results.

It will also help to reduce the effect of Bad-Data into SE. There are two types of meter redundancy in PSSE; global and local redundancy of a meter. Three different redundancy levels and their impact on the PSSE has already been discussed in the section 2.4.

Global redundancy is easy to calculate and shows the overall picture of the system. But on the other hand, the local redundancy requires a litter more calculations. The local redundancy of a meter can be found from K hat matrix in equation 3.11 [45]. If the diagonal entry of K matrix is large enough when compared to other off diagonal entries of a specific row than it can be implied that the local redundancy of that specific meter is week and the estimated value which belongs to that meter is determined solely by its meter reading [34]. If there is enough error in a meter reading, then estimated value of the meter will be affected and it will contain a large error. It may also effect other estimated values for a given data set.

$$LR(i) = N_{meas} - \sum_{t=1}^{N_{meas}} b(i,j) \tag{3.13}$$

$$\begin{bmatrix} b(i,j) = 1 & if & abs(K(i,i)/K(i,j)) \geq d \\ b(i,j) = 0 & & else \end{bmatrix} \tag{3.14}$$

where:

$LR(i)$ represent the local redundancy of ith meter location;

$K(i,i)$ and $K(i,j)$ are diagonal and off-diagonal entries of K;

N_{meas} is number of measurements;

$b(i,j)$ is binary number;

d is threshold value and has been considered 1000 for this thesis.

If $abs(K(i,i)/K(i,j)) \geq 1000$, then $b(i,j)$ will be 1, otherwise it will be zero. To get the value of $LR(i)$, the summation of all $b(i,j)$ will be subtracted from total number to measurements.

CHAPTER 4

MODELLING OF PMU VOLTAGE AND CURRENT PHASORS

In this thesis, both voltage and current phasors from PMUs have been incorporated into WLS, WLAV and LMR estimator to enhance the accuracy of the estimation process. The LMR estimator has been modified in particular along with investigation of tolerance parameter. This tolerance parameter has crucial significance and it makes LMR distinguish among other estimators because this parameter helps in rejection of unreliable measurements during the estimation process and it can be tuned for best estimation results. All of these estimators hold different objective functions for minimization of estimation error. PSSE is highly nonlinear problem with conventional power flow meters, power injection meters, and voltage magnitude meters. Jacobian matrix can be obtained by taking partial derivatives of measurement functions w.r.t state variables. After minimization of objective function, state variables are used to calculate power flows and power injections in all transmission lines and buses, respectively. The method to calculate Jacobian matrix is same for all of these algorithms, but they differ from each other for numerical method to compute and solve minimization equation. The static-state estimator is based on classical mathematical techniques such as estimation, detection, probability, statistics, and filtering. In this chapter, the main contributions to this thesis has been explained in detail with equations and algorithms.

4.1 Inclusion of Voltage and Current Phasors into PSSE

PSSE is playing a crucial role for secure, uninterrupted and smooth operation of power system since decades. State estimators are helping ISOs for security assessment and appropriate control and action to effectively manage the complete EMS. Robustness is one of the most important aspect while choosing a state estimator. Robustness of a state estimator is dependent upon measurement meter configuration and network topology of a system. So, the meter configuration should be such that; 1) a certain level of redundancy should be achieved for overall system observability 2) Bad-Data detection capabilities should be improved 3) and system should never be unobservable due to loss of any meter. The system will become completely unobservable if any critical meter has been lost. Conventional SCADA measurements are most commonly transmitted through RTU which is installed at selected substations. Nowadays, PMUs are becoming popular in power system monitoring and security assessment. PMUs are available at only few substations, because its installation cost is very high.

Once a PMU is installed into a system, the voltage phasor of the bus and current phasor of all incoming and outgoing transmission line can be measured accurately. In this thesis, these PMU phasors have been incorporated into existing SE algorithms and expectation was to gain a better estimation performance. When a phasor measurement is included into a state estimator, the weight of the phasor measurement has to be increased [10]. In WLS and WLAV, there is a weight matrix where any measurement can be assigned a specific weight easily. But there is no weight matrix or covariance matrix in LMR estimator. It has been found from simulation and analysis of this thesis, that reducing the tolerance value of

LMR estimator of any measurement is equivalent to increasing weight in WLS and WLAV. The tolerance for LMR estimator is well discussed in section 4.2.

It is required to build a relationship between branch current flows in transmission lines and state variables to incorporate current phasor into SE. The model, which has been adopted, will include all transmission line and transformers between buses. An ampere flow in a branch can be written as:

$$\begin{aligned} I_{ij,real} &= (g_{ij} + g_{si})V_i \cos(\theta_i) - g_{ij}V_j \cos(\theta_j) \\ &-(b_{ij} + b_{si})V_i \sin(\theta_i) + b_{ij}V_j \sin(\theta_j) \end{aligned} \tag{4.1}$$

$$\begin{aligned} I_{ij,imag} &= (g_{ij} + g_{si})V_i \sin(\theta_i) - g_{ij}V_j \sin(\theta_j) \\ &+(b_{ij} + b_{si})V_i \cos(\theta_i) - b_{ij}V_j \cos(\theta_j) \end{aligned} \tag{4.2}$$

where:

> $I_{ij,real}$ *and* $I_{ij,imag}$ are rectangular components of the branch current flowing between bus i *and* j;
>
> V_i, V_j, θ_i *and* θ_j are voltage magnitude and phase angle of bus i *and* j respectively;
>
> g_{ij} *and* b_{ij} are conductance and susceptance between bus i *and* j respectively;
>
> g_{si} *and* b_{sj} are shunt conductance of bus i *and* j respectively.

It is required to take partial derivative of branch current given in equations 4.1 and 4.2 w.r.t state variables, so that these can be incorporated into Jacobian matrix. Taking partial derivative of equations 4.1 and 4.2 w.r.t state variables for the current phasors are;

$$\frac{\partial I_{ij,real}}{\partial \theta_i} = -V_i[(g_{ij} + g_{si})\sin(\theta_i) + (b_{ij} + b_{si})\cos(\theta_i)] \tag{4.3}$$

$$\frac{\partial I_{ij,real}}{\partial V_i} = (g_{ij} + g_{si})\cos(\theta_i) - (b_{ij} + b_{si})\sin(\theta_i) \tag{4.4}$$

$$\frac{\partial I_{ij,imag}}{\partial \theta_i} = V_i[(g_{ij} + g_{si})\cos(\theta_i) - (b_{ij} + b_{si})\sin(\theta_i)] \tag{4.5}$$

$$\frac{\partial I_{ij,imag}}{\partial V_i} = (g_{ij} + g_{si})\sin(\theta_i) + (b_{ij} + b_{si})\cos(\theta_i) \tag{4.6}$$

$$\frac{\partial I_{ij,real}}{\partial \theta_j} = V_j(g_{ij}\sin(\theta_j) + b_{ij}\cos(\theta_j)) \tag{4.7}$$

$$\frac{\partial I_{ij,real}}{\partial V_j} = -g_{ij}\cos(\theta_j) + b_{ij}\sin(\theta_j) \tag{4.8}$$

$$\frac{\partial I_{ij,imag}}{\partial \theta_j} = V_j(-g_{ij}\cos(\theta_j) + b_{ij}\sin(\theta_j)) \tag{4.9}$$

$$\frac{\partial I_{ij,imag}}{\partial V_j} = -g_{ij}\sin(\theta_j) - b_{ij}\cos(\theta_j) \tag{4.10}$$

The Hybrid SE model is ready with all its basic equations and Jacobian matrix elements. Practically, PMU gives current measurements in polar form which can be called as direct measurements rather than rectangular form. However, it is much better to use current phasors in rectangular format, because the power flow meters and power injection meters are already in rectangular coordinates. All the measurements will be in rectangular coordinates for Jacobian matrix. So, the current measurements can be converted into rectangular coordinates and utilized for the estimation process. If direct measurements are converted into rectangular coordinated or indirect measurements, then error covariance value must be translated for indirect measurements. The relation between direct and indirect measurement is given by following equations.

$$I_{ij,real} = I_{ij} \cos\theta_{I_{ij}} \tag{4.11}$$

$$I_{ij,imag} = I_{ij} \sin\theta_{I_{ij}} \tag{4.12}$$

where:

I_{ij} is branch current magnitude between bus $i \text{ and } j$;

$\theta_{I_{ij}}$ is branch current phase angle between bus $i \text{ and } j$.

The standard deviation of translated measurements can be calculated from equations 4.13 and 4.14 [10]. Since the voltage phase angle is directly utilized into state estimator, so its standard deviation value can be set directly. The standard deviation values for all types of meters are given in section 5.1.

$$\begin{aligned}\sigma_{I_{ij,real}} &= \sqrt{\left(\frac{\partial I_{ij,real}}{\partial I_{ij}}\right)^2 \sigma_{I_{ij}}^2 + \left(\frac{\partial I_{ij,real}}{\partial \theta_{ij}}\right)^2 \sigma_{\theta_{I,ij}}^2} \\ &= \sqrt{\left(\cos\theta_{I_{ij}}\right)^2 \sigma_{I_{ij}}^2 + \left(I_{ij} \sin\theta_{I_{ij}}\right)^2 \sigma_{\theta_{I,ij}}^2}\end{aligned} \tag{4.13}$$

$$\begin{aligned}\sigma_{I_{ij,imag}} &= \sqrt{\left(\frac{\partial I_{ij,imag}}{\partial I_{ij}}\right)^2 \sigma_{I_{ij}}^2 + \left(\frac{\partial I_{ij,imag}}{\partial \theta_{ij}}\right)^2 \sigma_{\theta_{I,ij}}^2} \\ &= \sqrt{\left(\sin\theta_{I_{ij}}\right)^2 \sigma_{I_{ij}}^2 + \left(I_{ij} \cos\theta_{I_{ij}}\right)^2 \sigma_{\theta_{I,ij}}^2}\end{aligned} \tag{4.14}$$

where:

$\sigma_{I_{ij,real}}$ *and* $\sigma_{I_{ij,imag}}$ are standard deviations of real and imaginary parts of current flows respectively;

$\sigma_{I_{ij}} = 0.002p.u$ and $\sigma_{\theta_{I,ij}} = 0.0017rad$ are standard deviation of I_{ij} and $\theta_{I_{ij}}$ respectively.

4.1.1 Modified Weighted Least Square Estimator with Phasors

Weighted Least Square estimator has an objective function which minimizes the square of the error. Many estimation algorithms have been proposed like Least Square (LS), Weighted Least Absolute Value (WLAV), Iterative Reweighted Least Square (IRLS), Least Measurement Rejected (LMR), Least Trimmed Square (LTS), Least Median Square (LMS), etc. WLS provides better estimation results when subjected to only normally distributed errors in measurements but it collapses in the presence of even a single Bad-Data. WLS is most commonly used estimator in power industry and EMS and its mathematical formulation and modification to incorporate phasors is discussed in this section.

Traditional SE utilizes conventional SCADA measurements and its relation with system states variables is given below:

$$z = \begin{bmatrix} z_1 \\ z_2 \\ . \\ . \\ z_m \end{bmatrix} = \begin{bmatrix} h_1(x_1, x_2, ..., x_n) \\ h_2(x_1, x_2, ..., x_n) \\ . \\ . \\ h_m(x_1, x_2, ..., x_n) \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ . \\ . \\ e_m \end{bmatrix} = h\ (x) + e \tag{4.15}$$

where:

z is SCADA measurement vector and its size is $(m \; x \; 1)$;

$h(x) = [h_1(x), h_2(x), ..., h_m(x)]^T$ correspond to a vector of nonlinear function, which relates measurements to the state variables;

$e = [e_1, e_2, ..., e_m]^T$ is vector of error between estimated and measurements values and its size is $(m \; x \; 1)$;

$x = [x_1, x_2, ..., x_m]^T$ is state variables vector.

PSSE is a system of overdetermined nonlinear equations and must be solved as unconstrained WLS problem. For WLS, we need to minimize the sum of square of residuals:

$$\min J(x) = \sum_{i=1}^{n} \frac{|(z_i - h_i(x))|^2}{R_{ii}} \tag{4.16}$$

$$R_{ii} = diag\{\sigma_1^2, \sigma_2^2, ..., \sigma_m^2\} \tag{4.17}$$

$$\min J(x) = \left[z - h(x)\right]^T [R^{-1}] \left[z - h(x)\right] \tag{4.18}$$

WLS estimator assumes a set of measurement error variances whose reciprocals are commonly chosen as the weight for the measurements. This weight may represent different entities dependent upon the application. For example, the *R* matrix can represent meter accuracy, reliability or any other engineering perspective [33]. *R* will only be diagonal matrix, if no relation exists between different measurements and it will contain measurement variances. WLS is solved with measurement dependency on each other in [42].

For minimization of $J(x)$, the first order optimality condition of derivative must be satisfied. The derivative of Equation 4.18 is given below:

$$\frac{\partial J(x)}{\partial x} = -H^T R^{-1}[z - h(x)] = 0 \tag{4.19}$$

There is nonlinear relationship between power flow equations, power injection equations and state variables. So, we need an iterative technique to minimize $J(x)$. To minimize $J(x)$, its gradient must be equal to zero resulting.

All power flows and power injection equations are required to build up Jacobian matrix. Real and Reactive power injection at bus $i \text{ and } j$ can be represented by equations 4.20 and 4.21.

$$P_{inj} = V_i \sum_{j=1}^{n} V_j (g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}) \tag{4.20}$$

$$Q_{inj} = V_i \sum_{j=1}^{n} V_j (g_{ij} sin\theta_{ij} - b_{ij} cos\theta_{ij}) \tag{4.21}$$

where:

θ_{ij} is voltage phase angle between bus $i \text{ and } j$;

P_{inj} is active power injection at ith bus;

Q_{inj} is reactive power injection at ith bus.

The real and reactive power flow between transmission lines can be represented by the following equations;

$$P_{ij} = V_i^2(g_{si} + g_{ij}) - V_i V_j (g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}) \quad (4.22)$$

$$Q_{ij} = -V_i^2(b_{si} + b_{ij}) - V_i V_j (g_{ij} sin\theta_{ij} - b_{ij} cos\theta_{ij}) \quad (4.23)$$

where:

P_{ij} is active power flow between bus $i \ and \ j$;

Q_{ij} is reactive power flow between bus $i \ and \ j$;

The modified Jacobian after incorporating voltage and current phasors, which already have been explained in equations from 4.3 to 4.10, will be like;

$$H = \begin{bmatrix} \frac{\partial P_{ij}}{\partial \theta} & \frac{\partial P_{ij}}{\partial V} \\ \frac{\partial P_{ji}}{\partial \theta} & \frac{\partial P_{ji}}{\partial V} \\ \frac{\partial P_{inj}}{\partial \theta} & \frac{\partial P_{inj}}{\partial V} \\ \frac{\partial \theta}{\partial \theta} & \frac{\partial \theta}{\partial V} \\ \frac{\partial Q_{ij}}{\partial \theta} & \frac{\partial Q_{ij}}{\partial V} \\ \frac{\partial Q_{ji}}{\partial \theta} & \frac{\partial Q_{ji}}{\partial V} \\ \frac{\partial Q_{inj}}{\partial \theta} & \frac{\partial Q_{inj}}{\partial V} \\ \frac{\partial V}{\partial \theta} & \frac{\partial V}{\partial V} \\ \frac{\partial I_{ij,real}}{\partial \theta} & \frac{\partial I_{ij,real}}{\partial V} \\ \frac{\partial I_{ij,imag}}{\partial \theta} & \frac{\partial I_{ij,imag}}{\partial V} \\ \frac{\partial I_{ji,real}}{\partial \theta} & \frac{\partial I_{ji,real}}{\partial V} \\ \frac{\partial I_{ji,imag}}{\partial \theta} & \frac{\partial I_{ji,imag}}{\partial V} \end{bmatrix} \tag{4.24}$$

The detailed expressions for Jacobian elements are given below. The equations 4.25 to 4.28 are representing partial derivate of real and reactive power injections w.r.t state variables.

$$\begin{aligned} \frac{\delta P_{inj}}{\delta \theta_i} &= \sum_{j=1}^{N} V_i V_j (-g_{ij} sin\theta_{ij} + b_{ij} cos\theta_{ij}) - V_i^2 b_{si} \\ \frac{\delta P_{inj}}{\delta \theta_j} &= V_i V_j (g_{ij} sin\theta_{ij} - b_{ij} cos\theta_{ij}) \end{aligned} \tag{4.25}$$

$$\frac{\delta P_{inj}}{\delta V_i} = \sum_{j=1}^{N} V_j (g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}) + V_i g_{si}$$

$$\frac{\delta P_{inj}}{\delta V_j} = V_i (g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}) \tag{4.26}$$

$$\frac{\delta Q_{inj}}{\delta \theta_i} = \sum_{j=1}^{N} V_i V_j (g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}) - V_i^2 g_{si}$$

$$\frac{\delta Q_{inj}}{\delta \theta_j} = V_i V_j (-g_{ij} cos\theta_{ij} - b_{ij} sin\theta_{ij}) \tag{4.27}$$

$$\frac{\delta Q_{inj}}{\delta V_i} = \sum_{j=1}^{N} V_j (g_{ij} sin\theta_{ij} - b_{ij} cos\theta_{ij}) - V_i b_{si}$$

$$\frac{\delta Q_{inj}}{\delta V_j} = V_i (g_{ij} \sin\theta_{ij} - b_{ij} cos\theta_{ij}) \tag{4.28}$$

Equations 4.29 to 4.34 are representing partial derivate of real and reactive power flows w.r.t state variables between bus $i \text{ and } j$.

$$\frac{\delta P_{ij}}{\delta \theta_i} = V_i V_j (g_{ij} sin\theta_{ij} - b_{ij} cos\theta_{ij})$$

$$\frac{\delta P_{ij}}{\delta \theta_j} = -V_i V_j (-g_{ij} sin\theta_{ij} - b_{ij} cos\theta_{ij}) \tag{4.29}$$

$$\frac{\delta P_{ij}}{\delta V_i} = -V_j (g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}) + 2(g_{si} + g_{ij}) V_i$$

$$\frac{\delta P_{ij}}{\delta V_j} = -V_i (g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}) \tag{4.30}$$

$$\frac{\delta Q_{ij}}{\delta \theta_i} = -V_i V_j (g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}) \tag{4.31}$$

$$\frac{\delta Q_{ij}}{\delta \theta_j} = V_i V_j (g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}) \tag{4.32}$$

$$\frac{\delta Q_{ij}}{\delta V_i} = -V_j (g_{ij} sin\theta_{ij} - b_{ij} cos\theta_{ij}) - 2(b_{si} + b_{ij}) V_i \tag{4.33}$$

$$\frac{\delta Q_{ij}}{\delta V_j} = -V_i(g_{ij} sin\theta_{ij} - b_{ij} cos\theta_{ij})` \tag{4.34}$$

The elements correspond to partial derivate of voltage magnitude w.r.t state variables are in equation 4.35.

$$\frac{\delta V_i}{\delta V_i} = 1,\ \frac{\delta V_i}{\delta V_j} = 0,\ \frac{\delta V_i}{\delta \theta_i} = 0,\ \frac{\delta V_i}{\delta \theta_j} = 0 \tag{4.35}$$

Assuming at k_{th}iteration, $x_k$is the state vector for x_{k+1} next iteration can be calculated:

$$x_{k+1} = x_k + \Delta x = x_k + \left[[H]^T[R]^{-1}[H]\right]^{-1}[H]^T[R]^{-1}\begin{bmatrix} z_1 - h_1(x) \\ z_2 - h_1(x) \\ \cdots \\ \cdots \\ z_m - h_m(x) \\ \\ \\ \end{bmatrix} \tag{4.36}$$

where:

Δx is the state variable mismatch vector.

A unique solution for Δx can be computed if gain matrix $[H]^T[R]^{(-1)}[H]$ is non-singular or if H has full a column rank, i.e. $rank[H] = n$, where n is number of state variables. Iterative procedure terminates when Δx goes below a certain low threshold value, e.g. $1xe^{-4}$.

4.1.2 Modified Weighted Least Absolute Value Estimator with Phasors

In this section, the mathematical formulation of modified WLAV estimator is presented along with incorporation of voltage and current phasors. Usually, Linear Programming

(LP) solving approach like Simplex Method or Interior Point Method is used for WLAV estimation. The performance of WLAV estimator is very good for rejection of Bad-Data but it fails in the presence of leverage points [22]. The minimization objective function of WLAV estimator is given below.

$$f\left(x\right)=\sum_{i=1}^{m}\frac{\left|z_i-h_i\left(x\right)\right|}{\sigma_i} \tag{4.37}$$

where:

σ_i is standard deviation of ith measurement.

Optimization of function $f\left(x\right)$ is linear, so that the Taylor approximation $h\left(x\right)$ at the point x_0 is used, where x_0 is initial value of state variables.

$$\Delta z = H(x^o \Delta x + e) \tag{4.38}$$

$$\Delta z = z - h\left(x_0\right) \tag{4.39}$$

$$\Delta x = x - x^o \tag{4.40}$$

$$H(x^o) = \frac{\partial h\left(x^o\right)}{\partial x} \tag{4.41}$$

$$H = \begin{bmatrix} \frac{\partial P_{ij}}{\partial \theta} & \frac{\partial P_{ij}}{\partial V} \\ \frac{\partial P_{ji}}{\partial \theta} & \frac{\partial P_{ji}}{\partial V} \\ \frac{\partial P_{inj}}{\partial \theta} & \frac{\partial P_{inj}}{\partial V} \\ \frac{\partial \theta}{\partial \theta} & \frac{\partial \theta}{\partial V} \\ \frac{\partial Q_{ij}}{\partial \theta} & \frac{\partial Q_{ij}}{\partial V} \\ \frac{\partial Q_{ji}}{\partial \theta} & \frac{\partial Q_{ji}}{\partial V} \\ \frac{\partial Q_{inj}}{\partial \theta} & \frac{\partial Q_{inj}}{\partial V} \\ \frac{\partial V}{\partial \theta} & \frac{\partial V}{\partial V} \\ \frac{\partial I_{ij,real}}{\partial \theta} & \frac{\partial I_{ij,real}}{\partial V} \\ \frac{\partial I_{ij,imag}}{\partial \theta} & \frac{\partial I_{ij,imag}}{\partial V} \\ \frac{\partial I_{ji,real}}{\partial \theta} & \frac{\partial I_{ji,real}}{\partial V} \\ \frac{\partial I_{ji,imag}}{\partial \theta} & \frac{\partial I_{ji,imag}}{\partial V} \end{bmatrix} \tag{4.42}$$

$$|e_i| \leq \varepsilon_i \tag{4.43}$$

where:

e_i is absolute error;

ε_i is a threshold value.

It is to be assumed that absolute error will be less than a threshold value. The equation 4.43 can be divided into two equations by adding two nonnegative slack variables

$$e_i - l_i = -\varepsilon_i \tag{4.44}$$

$$e_i + l_i = \varepsilon_i \tag{4.45}$$

which can be written as

$$e_i = u_i - v_i \tag{4.46}$$

$$u_i = \frac{1}{2} l_i \tag{4.47}$$

$$v_i = \frac{1}{2} k_i \tag{4.48}$$

The ε_i is smaller, it is liked e_i is minimized. The objective function $f(x)$ will be changed to objective function $f^{'}(x)$.

$$f'(x) = \sum_{i=1}^{m} \frac{(u_i + v_i)}{\sigma_i} \tag{4.49}$$

$$\Delta z = H\,\Delta x_u - H\,\Delta x_v + u - v \tag{4.50}$$

$$\Delta x_u, \Delta x_v, u, v \geq 0 \tag{4.51}$$

$$\Delta x = \Delta x_u - \Delta x_v \tag{4.52}$$

Here is LP solving formulation

$$\min c^T.Y \tag{4.53}$$

Subject to:

$$A.Y = b \tag{4.54}$$

$$Y \geq 0 \tag{4.55}$$

$$c^T = \begin{bmatrix} 0_{2n} & 1_{2m} \end{bmatrix}; \tag{4.56}$$

$$0_{2n} = [0,\ldots,0]; \text{ a zero vector of order } (1\, x\, 2n) \tag{4.57}$$

$$\mathbf{1}_{2m} = [1,\ldots,1]; \text{ an all 1's vector of order } (1\, x\, 2m) \tag{4.58}$$

$$Y = [\Delta x_u \quad \Delta x_v \quad u \quad v]^T \tag{4.59}$$

$$A = [H \quad -H \quad I_{\text{m}} \quad -I_{\text{m}}] \tag{4.60}$$

$$b = \Delta z \tag{4.61}$$

This objective function $f^{'}(x)$ can be optimized linear programming and in this current work lp_solve () MATLAB package has been used.

4.1.3 Modified Least Measurement Rejected Estimator with Phasors

A novel robust SE technique has been proposed using mixed integer programming in [43] which correlates a specific tolerance value to each of the measurement in the system. For each measurement, a tolerance range must be defined which will help the estimator to reject unreliable or corrupted measurements during the estimation process. This robust estimation approach is invulnerable to leverage points even in pathological cases. The upper and lower tolerance range values can be defined separately or it can be symmetrical e.g. a power injection meter of 10MW has upper tolerance value of 0.5MW and lower tolerance value of 0.75MW, the measurement value from the power injection meter between (10.5MW and 9.25MW) will be considered as good. If the measurement value lies outside this range, the measurement will be suspected as corrupted or bad. This is an effective and trivial estimation approach and is known as Least Measurement Rejected (LMR) estimator and it is a variant of Least Median of Square (LMS) estimator. LMR estimator minimizes the number of rejected measurements with a fixed tolerance and its objective function is given below:

$$\min \sum_{i=1}^{n} k_i \tag{4.62}$$

$$z_i - t_i - Mk_i \leq y_i(x) \leq t_i + Mk_i + z_i \tag{4.63}$$

where:

n is number of measurements;

z_i is measurement from ith meter;

$y_i(x)$ is measurement equation of ith meter;

t_i is tolerance value of ith measurement;

k_i is binary value and it indicates weather the measurement error is within a specified tolerance limit or not;

M is arbitrary large scalar value.

In this paper, M =50000 has been used for IEEE 30 and IEEE 118 bus system. The equations 4.62 and 4.63 have been transformed into mixed integer programming problem and solved in MATLAB R2015a:

$$\min c^T.Y \tag{4.64}$$

$$A.Y \leq B \tag{4.65}$$

$$c^T = \begin{bmatrix} 0_{2n} & 1_{2m} \end{bmatrix} \tag{4.66}$$

$$A = \begin{bmatrix} H & -M \\ -H & -M \end{bmatrix} \tag{4.67}$$

$$B^T = \left[b+t, b-t\right]; b = \Delta z \tag{4.68}$$

$$Y^T = \left[\Delta x, k\right] \tag{4.69}$$

where

H is the Jacobian matrix formulated in equation 4.42.

4.2 Tolerance Parameter of LMR Estimator

In this thesis, the tolerance parameter '*t*' of LMR estimator has been investigated in depth to get better estimation results. This tolerance parameter is an important control parameter which helps in rejection of unreliable measurements. The LMR estimator is altered with the inclusion of phasors to make it capable of better dealing with Bad-Data. Iteratively, the appropriate tolerance has been achieved for meters which ensures the better performance of the estimation. There is need to tune tolerance whenever phasor measurements are included into the system. This approach of phasors inclusion and tuning tolerance parameter has successfully improved the estimation accuracy. Meanwhile, the performance of modified LMR estimator with tuned tolerance has been investigated for different single and multiple Bad-Data scenarios which proves the robustness of LMR estimator. For future work, it has been proposed that each of the meter should have an appropriate tolerance value which will help LMR estimator to reject the unreliable measurements during the estimation process and will ensure the higher efficiency of the state estimation.

4.3 Heuristic Placement of PMU

This thesis also investigated the importance of locating PMUs in a power system. When a PMU is placed at a bus, it will measure the voltage phasor and all incoming and outgoing current phasors at this bus. So, all the available phasor measurements from PMU has been used in state estimation. Two PMUs have been placed heuristically into the system. One PMU is fixed at reference bus while another PMU is located at different buses heuristically. The accuracy of the estimator depends upon the proper selection of the buses where the second PMU is to be placed. PMU provides highly accurate phasor measurements and this high accuracy is simulated using actual load flow values with lower standard deviation value. The standard deviation and measurement weight are reciprocal to each other, lower standard deviation means higher weights. The placement of PMU must be chosen very carefully so that the best performance of the estimation process is achieved. PMU placement at a bus having large number of connected branches will not guarantee the better estimation results.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Simulation System

Test cases for IEEE 14, IEEE 30 and IEEE 118 bus systems are prepared on observable heuristic approach. The test cases have different set of measurement types and different global redundancy level. Estimator algorithm development and modification is carried out at MATLAB platform in MATPOWER package. WLS is using Newton's method to solve SE iteratively, WLAV is being solved using Linear Programming (LP) solver named "lp_solve" and it is a freeware solver based on the revised simplex method and the Branch-and-Bound method for the integers. While LMR estimator has been implemented by Mixed Integer Programming approach in MALAB. MS Excel has been used to save data like; load flow data, simulated measurements, standard deviation of meters, measurement types and index of measurements. The input data from MS Excel has been uploaded to MATLAB using "xlsread" command where further processing has been carried out to separate necessary data. The output estimated solution has been saved in MS EXCEL from MATLAB using "xlswrite" command.

The line data, bus data, single line diagram and load flow solution of IEEE 14, 30 and 118 bus system has been taken from MATPOWER package and all this data is provided in Appendix A.

When a PMU is installed at a bus, it will provide voltage magnitude and phase angle of the bus as well as current phasors of all incoming and outgoing transmission lines connected to that bus. Five types of Bad-Data scenarios are considered in this thesis; 1) single Bad-Data as a power flow meter on a transmission line, 2) single Bad-Data as a power injection meter on bus, 3) single Bad-Data as a voltage magnitude meter on bus, 4) multiple non-interacting Bad-Data consist of a power flow meter, power injection meter and voltage magnitude meter, 5) interacting Bad-Data contains combination of power flow meter, power injection meter and voltage magnitude meters. While choosing interacting and non-interacting measurement, the sensitivity matrix is used carefully. The test cases before phasor measurements incorporation contains the following type of measurements listed in Table 5.1 and simulated measurement data of these meters is given in Appendix A for IEEE 14, IEEE 30 and IEEE 118 bus system.

Table 5.1 Measurement Types

Measurement Type	Description
P_{ij}	Real power flow from bus *i to j*
P_{ji}	Real power flow from bus *j to i*
P_{inj} .	Real power injection at bus *i*
Q_{ij}	Reactive power flow from bus *i to j*
Q_{ji}	Reactive power flow from bus *j to i*
Q_{inj}	Reactive power injection at bus *i*
V_i	Voltage magnitude at bus *i*

After incorporation of PMU phasor measurements, the following measurements have been added into existing test cases as listed in Table 5.2:

Table 5.2 Measurement Types from PMU

Measurement Type	Description
θ_i	Voltage Angle
$I_{ij,real}$	Real value of current flow from bus *i to j*
$I_{ij,imag}$	Imaginary value of current flow from bus *i to j*
$I_{ji,real}$	Real value of current flow from bus *j to i*
$I_{ji,imag}$	Imaginary value of current flow from bus *j to i*

The standard deviations of SCADA meters are given in Table 5.3 and the standard deviations of current phasors are calculated from equations 4.13 and 4.14, given in section 4.1. The standard deviation is used to calculate the weighting factor for WLS and WLAV algorithms. When PMUs are incorporated with WLS and WLAV, the weights of these specific meter readings are increased and the simulated measurements are considered as the actual load flow values obtained from the load flow solution. In LMR estimator, since there is no weighting factor in its formulation, the PMU phasor measurements are taken as actual load flow values and the tolerance parameter of these specific measurements are set to zero. In this case, the LMR estimator will try its best to provide the estimated values same as the actual values.

Table 5.3 Measurements Standard Deviation

Measurement Type	Sigma without PMU	Sigma with PMU
P_{ij} , P_{ji} , P_{inj}	0.02	0.0002
Q_{ij} , Q_{ji} , Q_{inj}	0.04	0.0004
V_i	0.01	0.0001

While simulating Bad-Data, the meter locations have been carefully selected so that it should not be a critical measurement. The performance evaluation of these estimators is based on Cumulative Estimated Error (CEE) indicator which is sum of absolute difference between actual values and estimated values. The lower the CEE, the better the performance of the estimator.

Another criterion for the performance evaluation of these estimators is the ability of rejection of Bad-Data (AOR). If the estimated value lies outside the ±3σ of actual value, the estimated value will be considered as bad estimation of specific meter. In normal distribution, the values lie within ±3σ are considered as good estimate.

5.2 IEEE 14 Bus System

The proposed approach for all three estimators has been tested on IEEE 14 bus system. The line data, bus data, single line diagram and load flow solution for IEEE 14 bus system are given Appendix A.1. The meter distribution details of the test case are given in Table 5.4 and simulated measurement data of these meters is given in Table A.4. The reference bus is slack bus 1. Beside the PMU is placed at slack bus location, another PMU is placed at other locations simultaneously to find the best location. The results for IEEE 14 bus system are explained in section 5.2.1 to 5.2.7 with graphs and tables. In IEEE 14 bus system, the full redundancy value is 4.15 with 122 SCADA meters. The test case considered in this thesis has only 56 SCADA meters with a global redundancy of 2.03. It has been ensured that system is completely observable. All the critical measurements and sets have been identified before simulating Bad-Data on different types of measurement meters. The detailed SE results are given in Appendix B.1.

Table 5.4 IEEE 14 Bus – Meter Distribution

Measurement Type	Number of measurements	Measurements Distributions
P_{ij}	11	'P1-2','P1-5','P2-3','P3-4','P4-7','P6-11','P6-13',

		'P7-8','P9-14','P12-13','P13-14'
P_{ji}	6	'P2-1','P3-2','P5-4','P11-6','P8-7','P13-12'
P_{inj} .	9	'P1','P2','P3','P6','P7','P9','P10','P12','P13'
Q_{ij}	11	'Q1-2','Q1-5','Q2-3','Q3-4','Q4-7','Q6-11', 'Q6-13','Q7-8','Q9-14','Q12-13','Q13-14'
Q_{ji}	6	'Q2-1','Q3-2','Q5-4','Q11-6','Q8-7','Q13-12'
Q_{inj}	8	'Q1','Q2','Q3','Q6','Q9','Q10','Q12','Q13'
V_i	5	'V1','V3', 'V4','V11','V13'

5.2.1 White Noise

First test case is on IEEE 14 bus system and measurement contains only white noise (i.e.

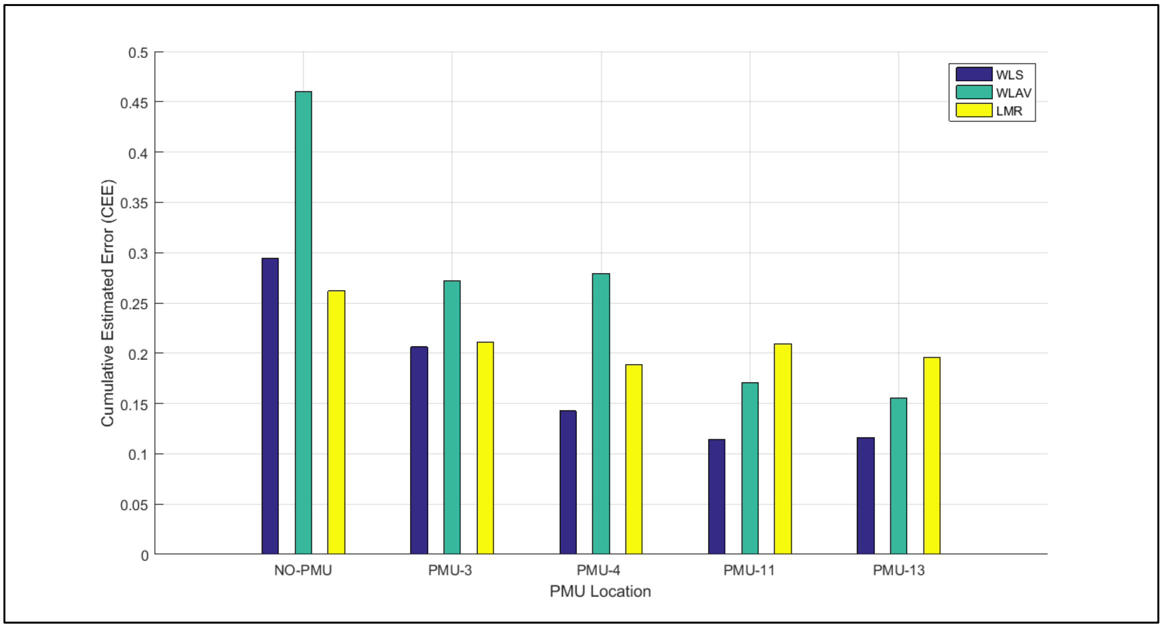

Figure 5.1 IEEE 14 Bus – White Noise

there is no Bad-Data in these measurements). White noise is added using equation 3.1. The estimation results with white noise for WLS, WLAV and LMR estimators are summarized in Figure 5.1 and shown in Table 5.5. The x-axis indicates different PMU locations while the y-axis shows Cumulative Estimated Error (CEE) indicator. The first values on x-axis presents the performance of the three estimators, when no PMU installed in the system. PMU-3, PMU-4, PMU-11 and PMU-13, indicates that a PMU is installed at bus 3 once and then moved to bus 4, 11 and 13 respectively. In all four cases, another PMU must be placed at bus 1 to act as the reference "slack" bus. It can be observed that when no PMU is installed in the system, the LMR estimator has the best performance and its CEE indicator is the lowest. Table 5.5 also shows the best value for tolerance parameter to get good estimation results for this system.

Table 5.5 IEEE 14 Bus – White Noise

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	0.294267	0.460172	0.261874	0.001
	AOR	0	0	0	
PMU-3	Indicator	0.206119	0.271712	0.210699	0.00061
	AOR	0	0	0	
PMU-4	Indicator	0.14247599	0.2793237	0.18906179	0.00061
	AOR	0	0	0	
PMU-11	Indicator	0.114023	0.171011	0.209595	0.0003
	AOR	0	0	0	
PMU-13	Indicator	0.115993	0.155317	0.195942	0.00025
	AOR	0	0	0	

The locations for votlatge magnitude meter are selected heuristically and shown in Table 5.4. The rest of voltge magnitude meters located at bus 2,5,6,7,8,9,10,12 and 14 have not been inlcuded in the test case because those meter locations are resulting higher CEE indicator. Another reason not to include those meters is to reduce the global redundancy of the test case because all the locations of a particalur power system are not connected with meters in parctice.

As described earlier, only two PMUs are considered to be placed in the system for this thesis. The first one is kept fixed at slack bus and the second one has considered to be relocated at different bus locations based on the number of branch connections that bus is having with other buses. The buses with only larger number of connnections are considered for second PMU installation. For example, bus 4 has got the maximum number of connections with other buses in IEEE 14 bus system.

5.2.2 Single Bad-Data as Power Flow Meter

In the following case, a single Bad-Data as power flow meter on transmission line between bus 2 and 3 has been simulated. The estimation results are shown in Figure 5.2 and

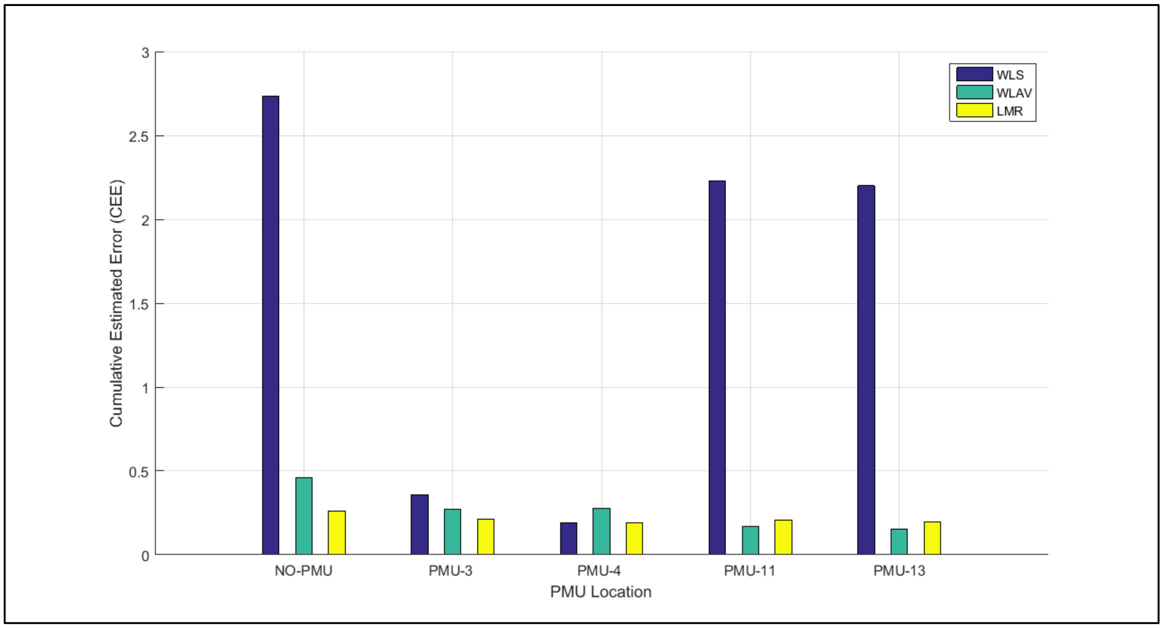

Figure 5.2 IEEE 14 Bus – Single Bad-Data as Power Flow Meter

summarized in Table 5.6. When the terminals of a meter are reversed during installation, the value of that meter will be strongest type of Bad-Data. In this type of Bad-Data, the magnitude of measurement will contain random noise but the polarity will be opposite. It may have a huge impact on state estimation.

Table 5.6 IEEE 14 Bus – Single Bad-Data as Power Flow Meter

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	2.731315	0.460172	0.261874	0.001
	AOR	8	0	0	
PMU-3	Indicator	0.35723	0.271712	0.210699	0.00061
	AOR	0	0	0	
PMU-4	Indicator	0.19041720	0.2793237	0.18906179	0.00061

	AOR	0	0	0	
PMU-11	Indicator	2.22821	0.171011	0.209595	0.0003
	AOR	7	0	0	
PMU-13	Indicator	2.199136	0.155317	0.195942	0.00025
	AOR	7	0	0	

For a single Bad-Data without any PMU, WLS estimator has failed to provide good estimation results, its CEE indicator is very high and there are total 8 rejections. But the performance of WLAV and LMR estimator is much better and they have zero AOR. From Table 5.6, it can be observed that the indicators for WLAV and LMR estimator are matching with previous case, which was white noise.

When PMU-3 is installed, the WLS has achieved a better level of performance. Its CEE indicator has secured a good value but still the WLAV and LMR are better choices for estimation.

But the WLS has failed again to provide good estimation results and there are total seven rejections, when PMU-11 is installed. It can be observed from Table 5.6, the WLAV is better than LMR estimator but both estimators have zero rejections. Unfortunately, the WLS estimator could not delivered good performance with PMU-13 as well, but the WLAV and LMR are providing very good estimation results.

5.2.3 Single Bad-Data as Power Injection Meter

In the following case, a single Bad-Data as reactive power injection meter has been applied on bus 3. The results are shown in Figure 5.3 and summarized in Table 5.7. It can be observed when there is no PMU in the system, LMR estimator has lowest CEE indicator while WLS has highest. When PMU is placed at bus 3, there is no big change in CEE indicator for LMR estimator but the performance of WLAV has become better. The CEE

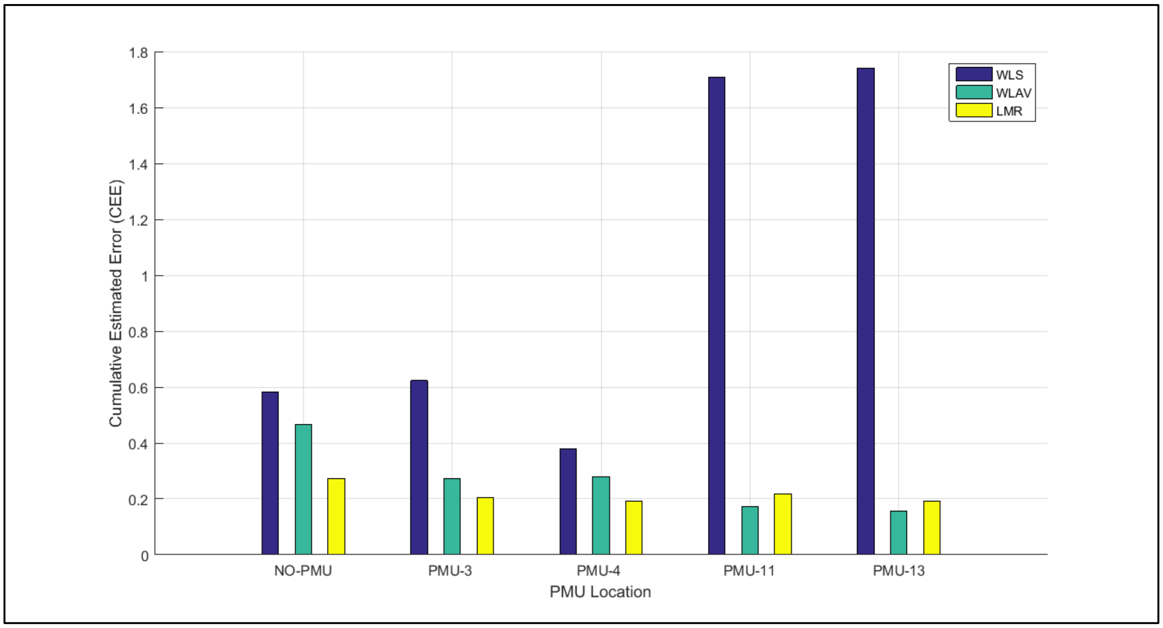

Figure 5.3 IEEE 14 Bus – Single Bad-Data as Power Injection Meter

indicator has reduced and there are still zero AOR. When PMU-11 is installed into the system, there is no big difference in the CEE indicator for WLAV and LMR. But the CEE indicator for WLS has increased w.r.t to the indicator at No-PMU. So, PMU-11 is not suitable installation location for the WLS estimator. For PMU-13, the indicators for WLAV and LMR are reduced when compared to PMU-11 but for the indicator for WLS has increased.

Table 5.7 IEEE 14 Bus – Single Bad-Data as Power Injection Meter

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	0.580854	0.466632	0.274081	0.001
	AOR	0	0	0	
PMU-3	Indicator	0.622768	0.271712	0.206069	0.00061
	AOR	0	0	0	
PMU-4	Indicator	0.3783458	0.2793237	0.19263530	0.00061
	AOR	0	0	0	
PMU-11	Indicator	1.709339	0.171011	0.219323	0.0003
	AOR	2	0	0	
PMU-13	Indicator	1.740105	0.155317	0.193345	0.00025
	AOR	2	0	0	

5.2.4 Single Bad-Data as Voltage Magnitude Meter

The results for single Bad-Data as voltage magnitude meter has been simulated. In this IEEE 14 bus test case, there are five voltage magnitude meters which are located at bus 1, 3, 4,11 and 13. The Bad-Data as voltage magnitude meter cannot be simulated on bus 1, because PMU will remain fix at bus 1 as reference. For other four locations, Bad-Data will be relocated, because there is limited choice to simulate Bad-Data on bus voltage

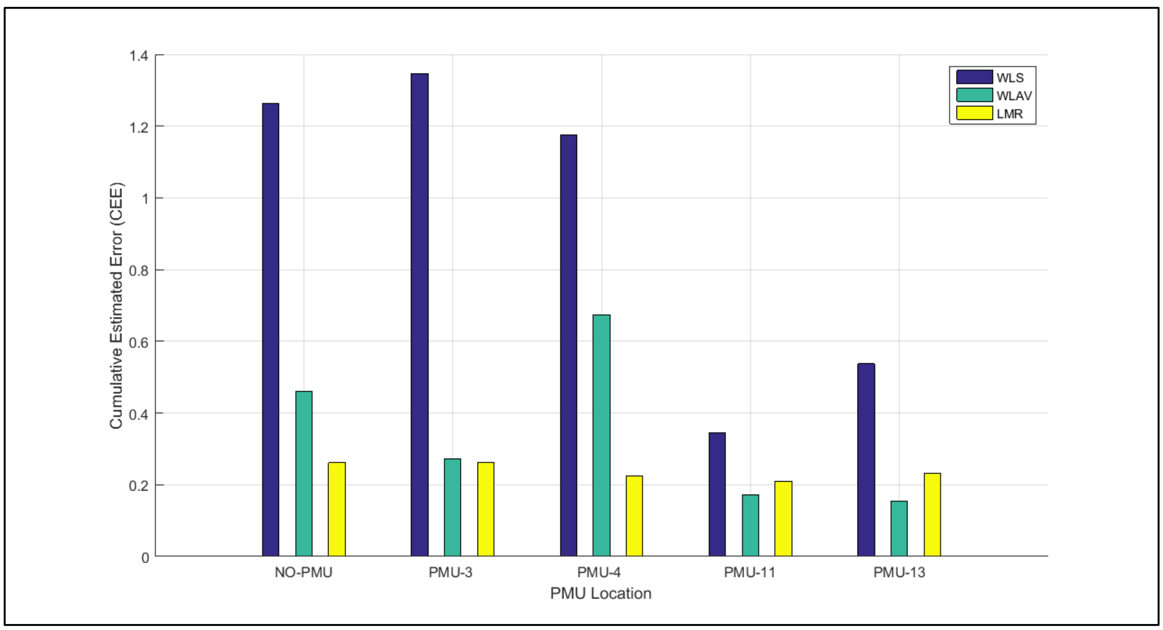

Figure 5.4 IEEE 14 Bus–Single Bad-Data as Voltage Magnitude Meter

magnitude meter. With No-PMU installation, the Bad-Data is simulated as voltage magnitude meter on bus 13. In this thesis, the Bad-Data as voltage magnitude meter is selected as $\pm 5\sigma$ of actual load flow value. The results can be observed from Figure 5.4 and Table 5.8. LMR estimator has best performance indicator with No-PMU and WLS has poor performance indicator. It can be observed from Table 5.8 that there are zero AOR from all estimators. The tolerance value of LMR estimator has been separately shown in last column.

Table 5.8 IEEE 14 Bus–Single Bad-Data as Voltage Magnitude Meter

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	1.26401	0.460172	0.261874	0.001
	AOR	0	0	0	
PMU-3	Indicator	1.347201	0.271712	0.261363	0.00061
	AOR	0	0	0	
PMU-4	Indicator	1.17494241	0.67490440	0.22440761	0.00061
	AOR	0	0	0	
PMU-11	Indicator	0.345019	0.171011	0.209595	0.0003
	AOR	0	0	0	
PMU-13	Indicator	0.537209	0.155317	0.231468	0.00025
	AOR	0	0	0	

When PMU-3 is installed into the system, the Bad-Data as voltage magnitude meter is simulated on bus 13. The CEE indicator for the WLAV estimator has improved and it comes closed to the CEE indicator for LMR estimator. But the CEE indicator for the WLS has increased. For PMU-11, the CEE indicators for all estimators have improved while Bad-Data has been simulated on bus 13. For PMU-13, the Bad-Data has been simulated as voltage magnitude on bus 3. Here, the WLAV has lowest indicator value.

5.2.5 Multiple Non-Interacting Bad-Data

The selection criteria for the multiple non-interacting and interacting Bad-Data has been explained in section 3.3. For multiple non-interacting Bad-Data, a power flow meter, a power injection meter and a voltage magnitude meter have been chosen to be simulated as Bad-Data. The polarity of measurement value is reversed for power flow meter and power injection meter, while ±5σ of actual value has been used to simulate voltage magnitude as

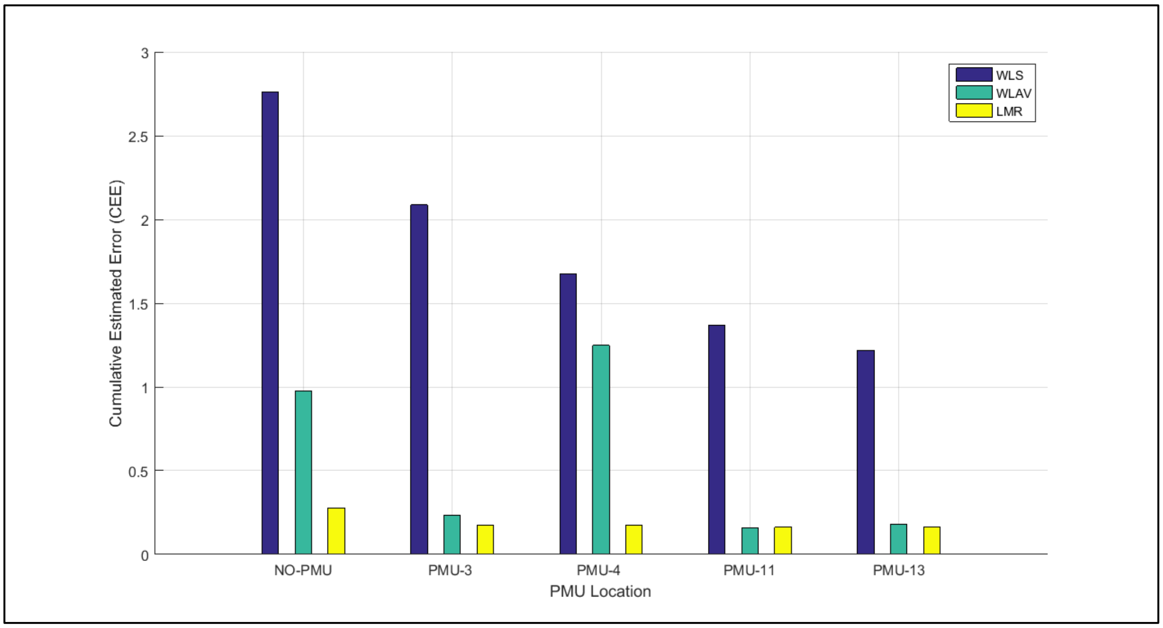

Figure 5.5 IEEE 14 Bus –Multiple Non-Interacting Bad-Data

Bad-Data. In this case, reactive power flow meter between bus 12 and 13, reactive power injection meter on bus 3 and voltage magnitude meter on bus 3 have been chosen to simulate as Bad-Data. The results are shown in Figure 5.5 and summarized in Table 5.9. With No-PMU installation, the CEE indicator is lowest for the LMR estimator. While the WLS and WLAV has much higher indicator. With PMU-3 installation into the system, the CEE indicator for all algorithms has reduced but it can be observed that there is still one AOR with WLS. For PMU-11 and PMU-13, the indicator for the LMR estimator is almost constant. It is to be noted here that with PMU-3 and PMU-11, the Bad-Data as voltage magnitude meter is on bus 13. When PMU-13 is installed into the system, the Bad-Data as voltage magnitude meter is on bus11.

Table 5.9 IEEE 14 Bus –Multiple Non-Interacting Bad-Data

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	2.762203	0.976	0.276552	0.001
	AOR	1	1	0	
PMU-3	Indicator	2.086409	0.233741	0.176657	0.00061
	AOR	1	0	0	
PMU-4	Indicator	1.67368734	1.24864141	0.1746269	0.00061
	AOR	1	0	0	
PMU-11	Indicator	1.367201	0.160173	0.162618	0.0003
	AOR	2	0	0	
PMU-13	Indicator	1.219871	0.178025	0.164058	0.00025
	AOR	0	0	0	

5.2.6 Multiple Interacting Bad-Data

For multiple interacting Bad-Data, the power flow meter between bus 12 and 13 and both the power injection meter and the voltage magnitude meter on bus 3 have been selected as

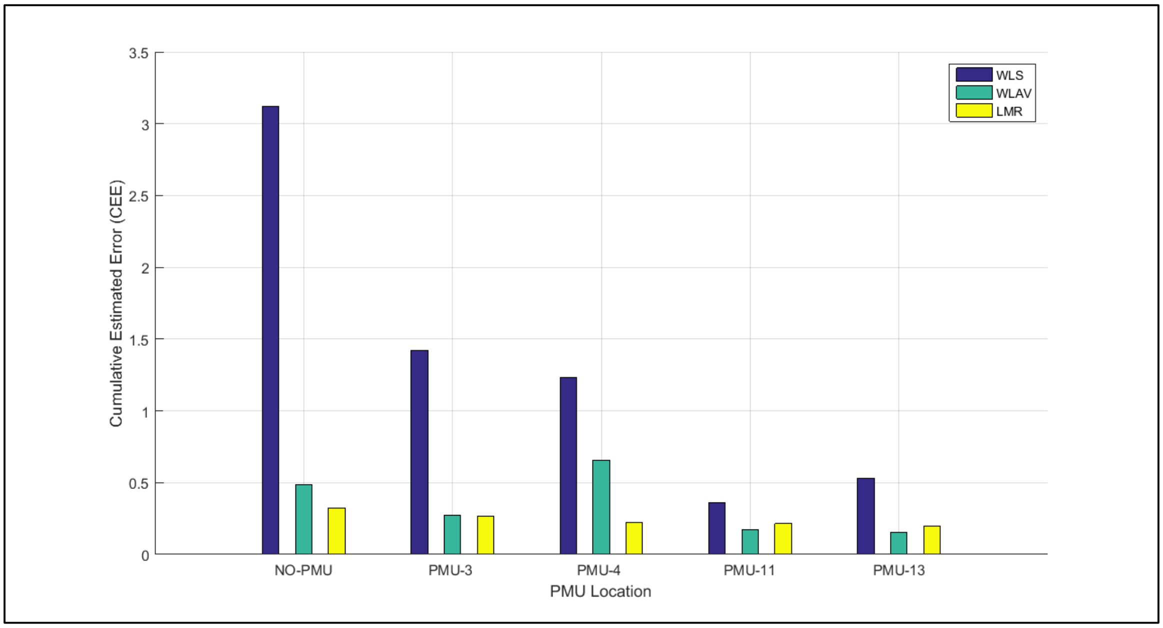

Figure 5.6 IEEE 14 Bus –Multiple Interacting Bad-Data

interacting measurements and simulated as Bad-Data. The results are plotted in Figure 5.6 and summarized in Table 5.10. It can be observed the CEE indicator is lowest for the LMR estimator when there is no PMU installed into the system. For PMU-3 and PMU-11, the voltage magnitude meter on bus 3 is chosen as Bad-Data because the Bad-Data cannot be simulated at PMU location. The CEE indicators for all three estimators has reduced and the AOR is also zero for all algorithms while LMR estimator has lowest CEE indicator. For PMU-11, the indicators for all the algorithms have reduced more w.r.t to the indicators at PMU-3. When PMU-13 is installed into the system, the voltage magnitude meter on bus 3 is simulated as Bad-Data while the power flow meter and the power injection meter locations are fixed as Bad-Data. For PMU-13, the WLAV has lowest CEE indicator.

Table 5.10 IEEE 14 Bus –Multiple Interacting Bad-Data

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	3.123583	0.485439	0.323285	0.001
	AOR	1	0	0	
PMU-3	Indicator	1.421223	0.272596	0.269202	0.00061
	AOR	0	0	0	
PMU-4	Indicator	1.23072929	0.65781910	0.22166898	0.00061
	AOR	0	0	0	
PMU-11	Indicator	0.358156	0.170948	0.215298	0.0003
	AOR	0	0	0	
PMU-13	Indicator	0.530768	0.155317	0.197302	0.00025
	AOR	0	0	0	

5.2.7 Results Discussion on IEEE 14 Bus

The inclusion of voltage and current phasors could improve the accuracy of estimator if proper location of PMU is selected. Without any PMU, the LMR estimator has lowest CEE indicator for all cases among the other estimators. With PMU installation, the LMR estimator has improved the accuracy of the estimated variables in all cases. The CEE indicators for the three algorithms have improved with PMU inclusion but LMR estimator has best performance. The indicators for WLAV and LMR are close to each other with PMU installation. The CEE indicator for WLS has also improved with PMU installation but this is not true for all cases. There were some cases where the indicator has increased with PMU installation for the WLS. For example, when the single Bad-Data as power injection meter has been simulated, the CEE indicator at PMU-11 and PMU 13 has increased.

5.3 IEEE 30 Bus System

The line data, bus data, single line diagram and load flow solution for IEEE 30 bus system are given Appendix A.2. The meter distribution details for the test case are given in Table 5.11 and simulated measurement data for these meters is given in Table A.8. The reference bus is Slack bus 1 and its phase angle value is zero degree. In IEEE 30 bus system, the full redundancy value is 4.3 with 254 SCADA meters. The test case considered in this thesis has only 126 SCADA meters with a global redundancy of 2.13. There are total 14 voltage magnitude meters in the test case, so there is wide-ranging choice for PMU placement. In all PMU placement cases, one PMU is placed at bus 1 to act as the reference "slack" bus. The second location is selected randomly for PMU installation. It has been ensured that system is completely observable. All the critical measurements and sets have been identified before simulating Bad-Data on different types of measurement meters. The detailed SE results are given in Appendix B.2.

Table 5.11 IEEE 30 Bus – Meter distribution

Measurement Type	Number of measurements	Meters Distribution

P_{ij}	25	'PF 1-3','PF 2-4','PF 2-5','PF 4-6','PF 5-7','PF 6-7' 'PF 6-8','PF 6-9','PF 6-10','PF 9-11','PF 12-13', 'PF 12-14','PF 12-16','PF 14-15','PF 15-18' 'PF 18-19','PF 10-17','PF 22-24','PF 23-24' 'PF 24-25','PF 25-26','PF 25-27','PF 28-27' 'PF 27-30','PF 29-30'
P_{ji}	16	'PT 2-1','PT 4-3','PT 6-2','PT 10-9','PT 12-4', 'PT 15-12','PT 20-19'.'PT 20-10','PT 21-10' 'PT 22-21','PT 23-15'.'PT 24-22','PT 24-23' 'PT 27-28','PT 30-29'.'PT 28-8'
P_{inj}	16	'PG-1','PG-2','PG-4','PG-5','PG-7','PG-9' 'PG-10','PG-14','PG-15'.'PG-16','PG-18','PG-19' 'PG-21','PG-24','PG-29'.'PG-30'
Q_{ij}	24	'QF 1-3','QF 2-4','QF 2-5','QF 4-6','QF 5-7','QF 6-7' 'QF 6-8','QF 6-9','QF 9-11','QF 12-13','QF 12-14' 'QF 12-16','QF 14-15','QF 15-18','QF 18-19', 'QF 10-17','QF 22-24','QF 23-24','QF 24-25', 'QF 25-26','QF 25-27','QF 28-27','QF 27-30' 'QF 29-30'
Q_{ji}	16	'QT 2-1','QT 4-3','QT 6-2','QT 10-9','QT 12-4', 'QT 15-12','QT 20-19','QT 20-10','QT 21-10' 'QT 22-21','QT 23-15','QT 24-22','QT 24-23' 'QT 27-28','QT 30-29','QT 28-8'
Q_{inj}	15	'QG-1','QG-2','QG-4','QG-5','QG-7','QG-9' 'QG-10','QG-14','QG-15','QG-16','QG-18','QG-19' 'QG-21','QG-24','QG-30'
V_i	14	'Vm-1','Vm-3','Vm-4','Vm-5','Vm-8','Vm-10' 'Vm-12','Vm-18','Vm-21','Vm-24','Vm-25','Vm-26' 'Vm-28','Vm-29'

5.3.1 White Noise

The measurements have been simulated from equation 3.1 and the actual values of power flow meters, power injection meters and voltage magnitude meters have been taken from load flow program in MATPOWER and are available in Appendix A.2. In this test case, only white noise has been simulated as meter readings. The estimation results are shown

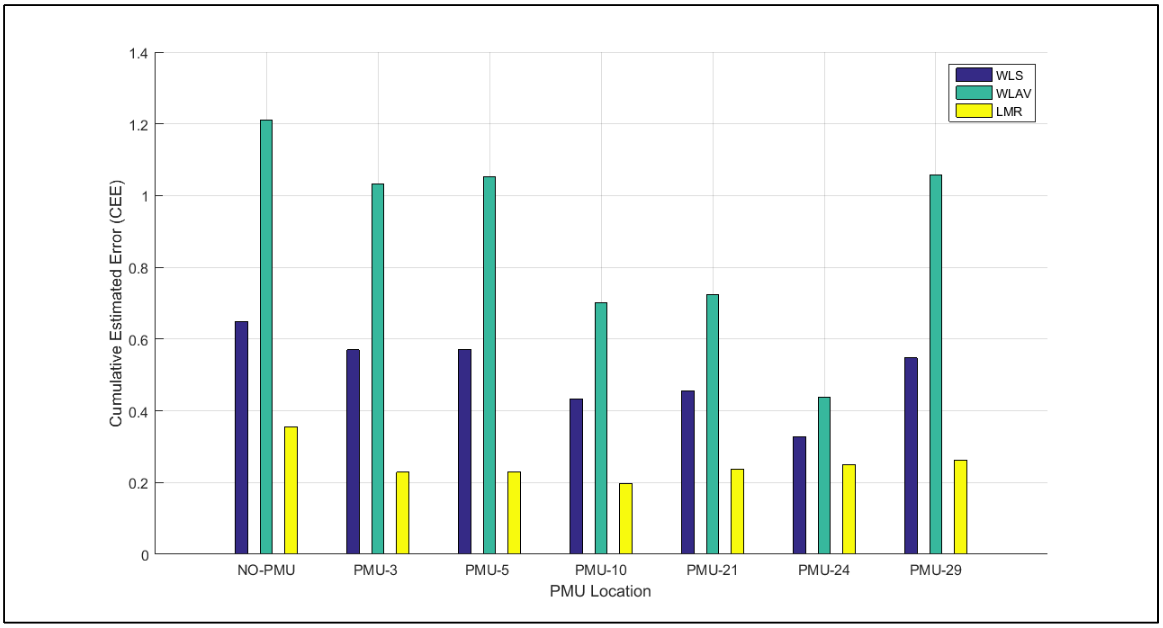

Figure 5.7 IEEE 30 Bus – White Noise

in Figure 5.7 and summarized in Table 5.12.

The locations for votlatge magnitude meter are selected heuristically and shown in Table 5.11 for IEEE 30 bus system. The rest of voltge magnitude meters located at other bus have not been inlcuded in the test case as those meter locations are resulting higher CEE indicator. The second reason is to reduce the global redundancy of the test case because all the locations of a particalur power system are not connected with meters in parctice.

As described earlier, only two PMU are considered to be placed in the system for this thesis. The first one is kept fixed at slack bus and the second one has considered to be relocated at different bus locations based on the number of branch connections that bus is having with other buses. The buses with only larger number of connnections are considered for second PMU installation.

It can be observed that with No-PMU the CEE indicator is lowest for the LMR estimator and highest for WLAV. When PMU-3 is installed into the system, the CEE indicator for all the estimators have improved but the LMR estimator has best performance, its CEE indicator is lowest and the AOR is zero for all the estimators. For PMU-5 and PMU-10, the CEE indicator has reduced for the WLAV and WLS. At PMU-24, the indicator for WLAV and WLS is lowest value w.r.t the indicator for No-PMU but still, the LMR estimator has lowest CEE indicator in comparison with the WLAV and WLS. For PMU-29, the CEE indicator for both the WLS and WLAV has increased w.r.t the indicator at PMU-24. In this test case, the LMR estimator has best performance indicator with or without PMU.

Table 5.12 IEEE 30 Bus – White Noise

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	0.648512	1.210794	0.355086	0.001
	AOR	0	0	0	
PMU-3	Indicator	0.569657	1.031549	0.228488	0.0005
	AOR	0	0	0	
PMU-5	Indicator	0.570668	1.053072	0.230013	0.0004
	AOR	0	0	0	
PMU-10	Indicator	0.432106	0.700268	0.197844	0.0004
	AOR	0	0	0	
PMU-21	Indicator	0.455055	0.724452	0.238346	0.0001
	AOR	0	0	0	
PMU-24	Indicator	0.327814	0.437295	0.24899	0.0001
	AOR	0	0	0	
PMU-29	Indicator	0.547293	1.056835	0.263268	0.0001
	AOR	0	0	0	

5.3.2 Single Bad-Data as Power Flow Meter

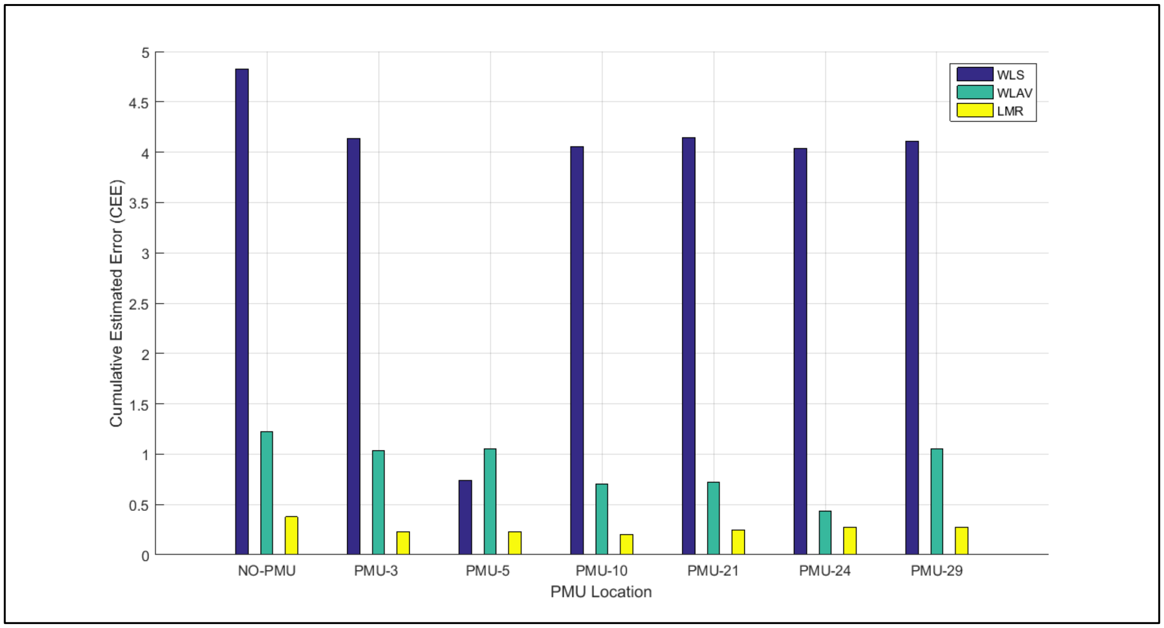

Figure 5.8 IEEE 30 Bus – Single Bad-Data as Power Flow Meter

A single Bad-Data as real power flow meter on transmission line between bus 2 and 5 has been simulated. The results are shown in Figure 5.8 and summarized in Table 5.13. When no PMU is installed into the system, the CEE indicator for LMR estimator is lowest and WLS has the highest value of the CEE indicator. With the installation of PMU-3, the CEE indicator for all estimator algorithms have improved but the CEE indicator for WLS could not reach to the indicator value of WLAV and LMR. There is drastic change in the CEE indicator value of WLS estimator when PMU-5 is installed into the system. But for PMU-10 to PMU-29, the CEE indicator for WLS is high and it can be observed that AOR is also high for the WLS at all locations. While the CEE indicator for WLAV is lowest at PMU-24 when compared with its own indicator value at other locations or with WLS. The LMR estimator has lowest indicator value at all PMU locations and even without PMU. So overall, the LMR estimator has very good performance indicator value with zero rejections in the presence of single Bad-Data as power flow meter.

Table 5.13 IEEE 30 Bus – Single Bad-Data as Power Flow Meter

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	4.82828	1.21920	0.37640	0.001
	AOR	6	0	0	
PMU-3	Indicator	4.13870	1.03154	0.23069	0.0005
	AOR	6	0	0	
PMU-5	Indicator	0.74216	1.05307	0.22960	0.0004
	AOR	0	0	0	
PMU-10	Indicator	4.05475	0.70026	0.20395	0.0004
	AOR	6	0	0	
PMU-21	Indicator	4.14554	0.72445	0.24379	0.0001
	AOR	6	0	0	
PMU-24	Indicator	4.03825	0.43729	0.27215	0.0001
	AOR	6	0	0	
PMU-29	Indicator	4.10702	1.05683	0.27424	0.0001
	AOR	6	0	0	

5.3.3 Single Bad-Data as Power Injection Meter

A single Bad-Data as real power injection meter is simulated on bus 2. The estimation results are shown in Figure 5.9 and summarized in Table 5.14. With NO-PMU, the LMR estimator has best performance indicator in comparison with the CEE indicators of WLS

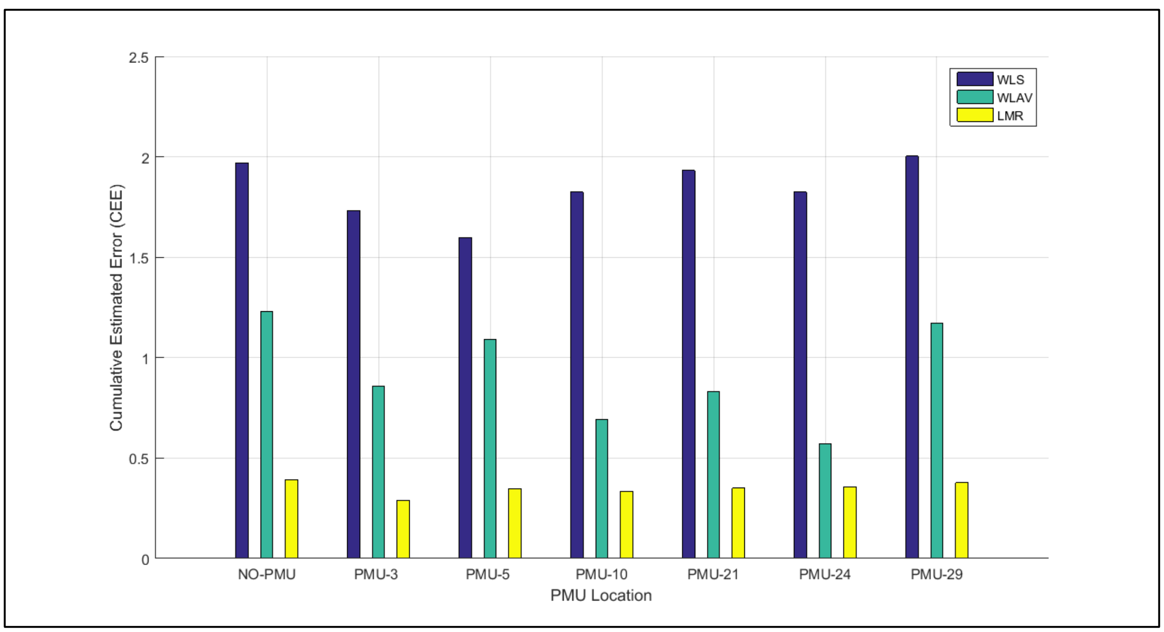

Figure 5.9 IEEE 30 Bus – Single Bad-Data as Power Injection Meter

and WLAV. When PMU-3 is installed into the system, the CEE indicators of all the algorithms have improved. The LMR estimator has lowest indicator value while WLS has highest indicator value. But with PMU installation, the AOR is zero, which was previously 1. At PMU-5, the indicator for WLS has reduced while for WLAV it has increased and all the algorithms have zero rejections. At PMU-24, the WLAV has the lowest indicator value when compared with its own values. The LMR estimator has shown itself as best state estimator at all locations with zero rejections.

Table 5.14 IEEE 30 Bus – Single Bad-Data as Power Injection Meter

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	1.971279	1.229494	0.393294	0.001
	AOR	1	0	0	
PMU-3	Indicator	1.731408	0.860043	0.2891	0.0005
	AOR	0	0	0	
PMU-5	Indicator	1.597375	1.092919	0.34625	0.0004
	AOR	0	0	0	
PMU-10	Indicator	1.824141	0.694344	0.33541	0.0004
	AOR	0	0	0	
PMU-21	Indicator	1.931374	0.829865	0.349802	0.0001
	AOR	0	0	0	
PMU-24	Indicator	1.824047	0.571833	0.357492	0.0001
	AOR	0	0	0	
PMU-29	Indicator	2.002806	1.170319	0.37663	0.0001
	AOR	0	0	0	

5.3.4 Single Bad-Data as Voltage Magnitude Meter

In this test case, a single Bad-Data as voltage magnitude meter is simulated on bus 12. The Bad-Data which is +5σ of actual value has been simulated for voltage magnitude meter. It is to notice here that voltage magnitude meter location for Bad-Data simulation is fixed in this test case while it was changing in IEEE 14 bus system. The results are shown in Figure

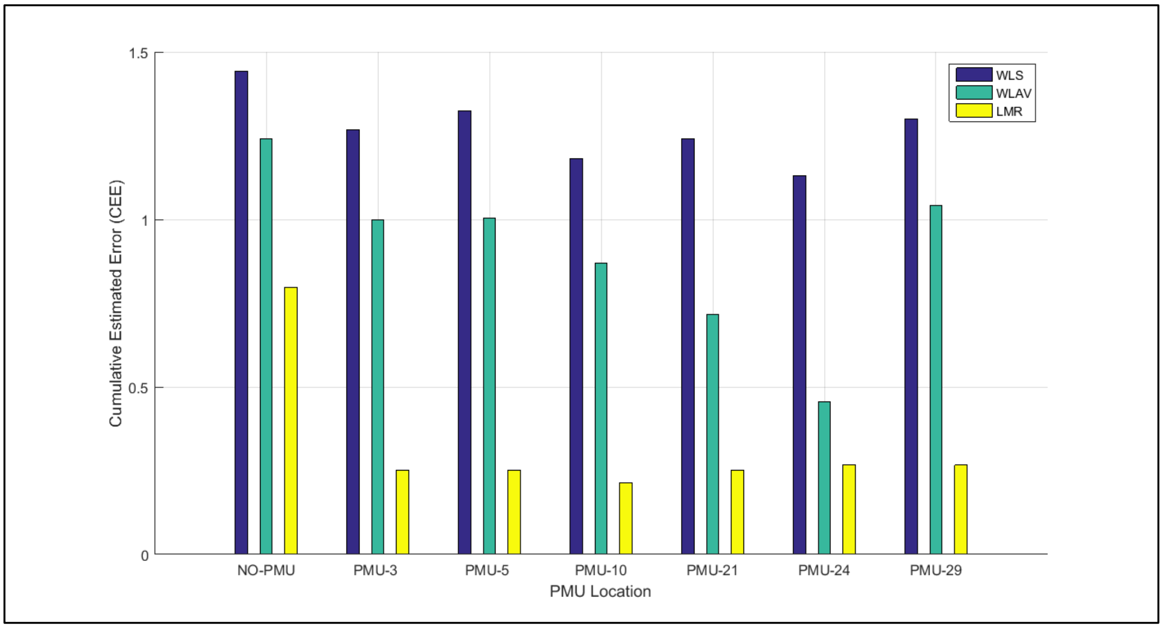

Figure 5.10 IEEE 30 Bus – Single bad-data as Voltage Magnitude Meter

5.10 and summarized in Table 5.15. The LMR estimator has the lowest and WLS has the highest value for CEE indicator without any PMU installed into the system. When PMU-3 is installed, the CEE indicator for LMR estimator has more improved and again it's the lowest value in comparison with WLS and WLAV. For PMU-5, the performance indicator for WLAV and WLS have also improved. For PMU-24, the indicator value of the WLS and WLAV is lowest when compared with their own previous value of this test case. While the indicator value for LMR estimator is lowest thought the graph with zero rejections.

Table 5.15 IEEE 30 Bus – Single Bad-Data as Voltage Magnitude Meter

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	1.441382	1.241597	0.796171	0.001
	AOR	0	0	0	
PMU-3	Indicator	1.266889	0.998613	0.252194	0.0005
	AOR	0	0	0	
PMU-5	Indicator	1.323713	1.004146	0.250518	0.0004
	AOR	0	0	0	
PMU-10	Indicator	1.182228	0.868596	0.213789	0.0004
	AOR	0	0	0	
PMU-21	Indicator	1.241198	0.716203	0.252375	0.0001
	AOR	0	0	0	
PMU-24	Indicator	1.130659	0.455328	0.266631	0.0001
	AOR	0	0	0	
PMU-29	Indicator	1.29891	1.040741	0.266334	0.0001
	AOR	0	0	0	

5.3.5 Multiple Non-Interacting Bad-Data

The multiple non-interacting Bad-Data location has been carefully selected from sensitivity matrix. The measurements combination consists of the real power flow meter between bus 2 and 4, the real power injection meter on bus 5 and the voltage magnitude meter on bus 12 have been simulated as Bad-Data. The results plot is shown in Figure 5.11 and summarized in Table 5.16. It can be observed that the LMR estimator has lowest CEE indicator value with NO-PMU. While WLS has the highest CEE indicator. When PMU-3 is placed into the system, there is an improvement into the indicator values for all the algorithms. For WLS, this change is more obvious when PMU-5 is installed into the system and its indicator value has dropped drastically. This is the lowest indicator value for the WLS when compared with other CEE values for this test case. The indicator value for

WLAV has also improved with PMU incorporation but the LMR estimator has overall best performance at all locations.

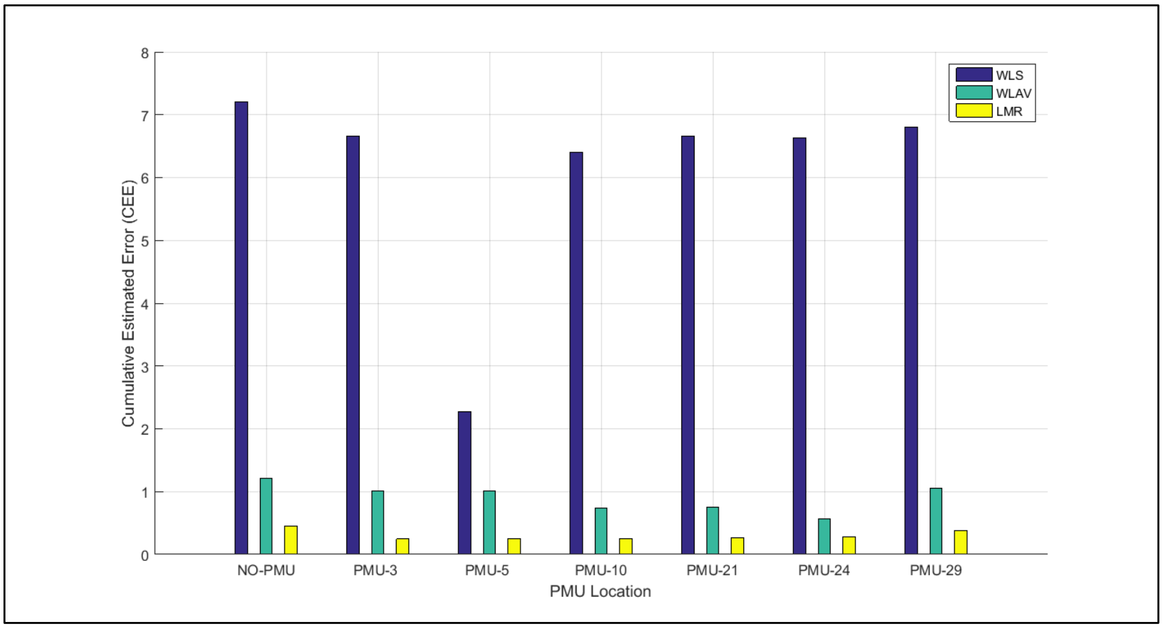

Figure 5.11 IEEE 30 Bus – Multiple Non-Interacting Bad-Data

Table 5.16 IEEE 30 Bus – Multiple Non-Interacting Bad-Data

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	7.206063	1.21647790	0.45488209	0.001
	AOR	7	0	0	
PMU-3	Indicator	6.655750	1.00442451	0.24449189	0.0005
	AOR	6	0	0	
PMU-5	Indicator	2.273485	1.01717019	0.24861598	0.0004
	AOR	0	0	0	
PMU-10	Indicator	6.406888	0.74455928	0.25550734	0.0004
	AOR	6	0	0	
PMU-21	Indicator	6.658079	0.75739376	0.26108258	0.0001
	AOR	6	0	0	
PMU-24	Indicator	6.632358	0.56826479	0.27915031	0.0001
	AOR	6	0	0	
PMU-29	Indicator	6.802784	1.05045237	0.37603837	0.0001
	AOR	6	0	0	

5.3.6 Multiple Interacting Bad-Data

For the multiple interacting Bad-Data, the reactive power flow meter on transmission line between bus 6 and 9, the reactive power injection meter on bus 24 and the voltage magnitude meter on bus 12 have been selected from sensitivity matrix. The output results are plotted in Figure 5.12 and summarized in Table 5.17. It can be observed that the CEE indicator is again lowest without any PMU, as it was in all previous cases. Like previous cases of IEEE 30 bus system, the indicator for the WLS is highest without any PMU

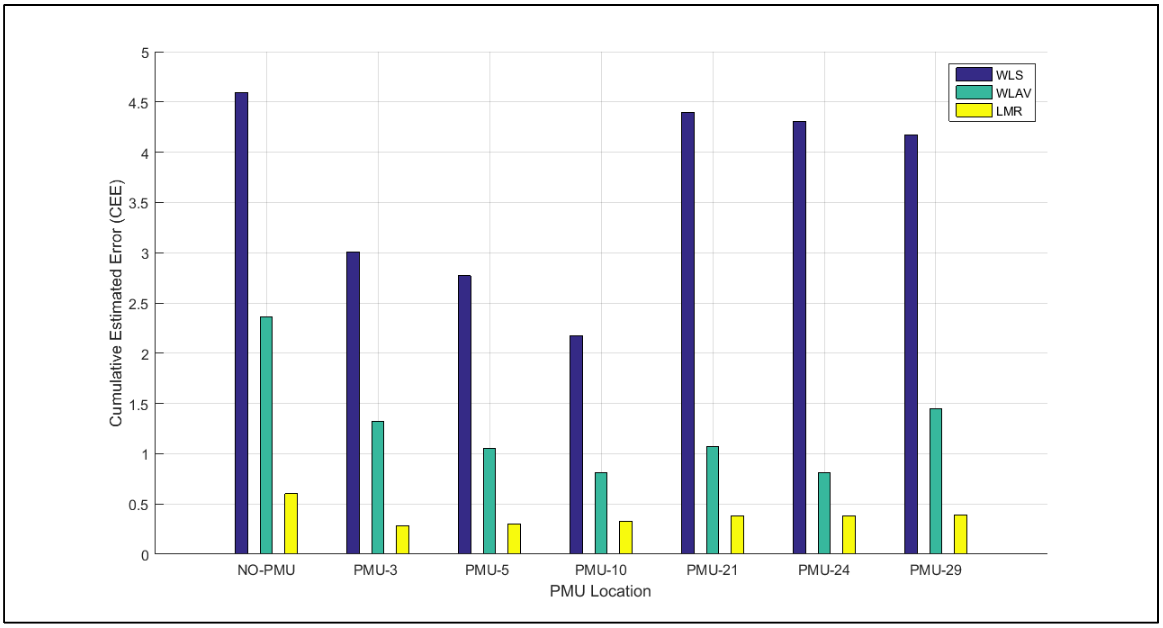

Figure 5.12 IEEE 30 Bus – Multiple Interacting Bad-Data

installation. With PMU-3, the indicator for all the algorithms have improved but there are rejections by the WLS estimator. The LMR estimator has lowest CEE indicator value with zero rejections at all locations. There is one rejection by the WLAV with NO-PMU.

Table 5.17 IEEE 30 Bus – Multiple Interacting Bad-Data

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	4.591357	2.362388	0.601762	0.001
	AOR	4	1	0	

PMU-3	Indicator	3.004764	1.322283	0.279296	0.0005
	AOR	2	0	0	
PMU-5	Indicator	2.769463	1.053088	0.303344	0.0004
	AOR	1	0	0	
PMU-10	Indicator	2.170788	0.808308	0.32935	0.0004
	AOR	2	0	0	
PMU-21	Indicator	4.398649	1.068944	0.383545	0.0001
	AOR	3	0	0	
PMU-24	Indicator	4.303892	0.811491	0.384068	0.0001
	AOR	3	0	0	
PMU-29	Indicator	4.169063	1.450612	0.38895	0.0001
	AOR	3	0	0	

5.3.7 Results Discussion on IEEE 30 Bus

The inclusion of voltage and current phasors could improve the accuracy of estimator if proper location of PMU is selected. Without any PMU, the LMR estimator has lowest CEE indicator for all cases among the other estimators. With PMU installation, the LMR and WLAV have improved the accuracy of the estimated variables in all cases. But LMR estimator has the best performance in all the test cases among all estimators. In all the cases, with and without PMU installation, the LMR estimator has best performance indicator value and minimum rejections.

5.4 IEEE 118 Bus System

The line data, bus data, single line diagram and load flow solution for IEEE 118 bus system are given Appendix A.3. The meter distribution for the test case has been shown in Table 5.18 and simulated measurement data for these meters is given in Table A.12. The full redundancy value is 4.67 with 1098 SCADA meters in the IEEE 118 bus system. The test case considered in this thesis has only 441 SCADA meters with a global redundancy of

1.87. There are total 61 voltage magnitude meters, so there is broader choice PMU installation. The PMU are installed on randomly chosen buses. It is to be noted here that the slack bus is 69 and voltage phase angle is 30 degrees in IEEE 118 bus system. One PMU is fixed on bus number 69 as reference and second PMU is relocated at different locations. It has been ensured that system is completely observable. All the critical measurements and sets have been identified before simulating Bad-Data on different types of measurement meters. The detailed SE results are given in Appendix B.3.

Table 5.18 IEEE 118 Bus – Meter Distribution

Measurement Type	Number of measurements	Measurements Distribution
P_{ij}	68	'PF 1-2','PF 3-5','PF 5-6','PF 6-7','PF 9-10','PF 4-11' 'PF 5-11','PF 2-12','PF 7-12','PF 12-14','PF 14-15', 'PF 17-18','PF 21-22','PF 23-24','PF 28-29', 'PF 30-17','PF 17-31'.'PF 23-32','PF 34-36' 'PF 37-40','PF 39-40'.'PF 40-41','PF 43-44' 'PF 34-43','PF 46-48'.'PF 45-49','PF 52-53' 'PF 54-55','PF 56-57','PF 50-57','PF 51-58' 'PF 59-60','PF 60-62','PF 64-65','PF 62-67' 'PF 65-68','PF 47-69','PF 71-72','PF 71-73' 'PF 69-75','PF 74-75','PF 76-77','PF 78-79' 'PF 81-80','PF 77-82','PF 84-85','PF 86-87' 'PF 85-88','PF 91-92','PF 92-93','PF 94-95' 'PF 82-96','PF 92-100','PF 95-96','PF 98-100' 'PF 99-100','PF 100-101','PF 101-102','PF 100-106' 'PF 105-108','PF 108-109','PF 109-110','PF 17-113' 'PF 27-115','PF 114-115','PF 12-117','PF 75-118' 'PF 76-118'
P_{ji}	66	'PT 11-12','PT 11-13','PT 13-15','PT 15-17', 'PT 18-19','PT 20-21','PT 21-22','PT 22-23' 'PT 23-25','PT 26-25','PT 27-28','PT 8-30' 'PT 29-31','PT 19-34','PT 35-37','PT 33-37' 'PT 30-38','PT 40-42','PT 41-42','PT 46-47' 'PT 42-49','PT 42-49','PT 48-49','PT 49-50' 'PT 49-51','PT 51-52','PT 49-54','PT 54-56' 'PT 55-56','PT 56-58','PT 54-59','PT 56-59' 'PT 59-61','PT 60-61','PT 63-59','PT 63-64' 'PT 49-66','PT 62-66','PT 65-66','PT 66-67' 'PT 49-69','PT 68-69','PT 24-70','PT 24-72'

		'PT 70-74','PT 69-77','PT 75-77','PT 79-80' 'PT 82-83','PT 85-86','PT 86-87','PT 88-89', 'PT 89-90','PT 92-94','PT 94-96','PT 80-98' 'PT 94-100','PT 96-97','PT 100-103','PT 104-105' 'PT 105-105','PT 106-107','PT 108-109','PT 32-113' 'PT 32-114','PT 68-116'
P_{inj}.	55	'PG-3','PG-4','PG-8','PG-9','PG-12','PG-13' 'PG-15','PG-16','PG-19','PG-20','PG-24','PG-25' 'PG-30','PG-31','PG-33','PG-35','PG-36','PG-38' 'PG-42','PG-44','PG-46','PG-47','PG-49','PG-52' 'PG-53','PG-54','PG-55','PG-61','PG-63','PG-64' 'PG-66','PG-68','PG-70','PG-71','PG-77','PG-79' 'PG-81','PG-83','PG-85','PG-86','PG-90','PG-92' 'PG-96','PG-97','PG-98','PG-99','PG-102','PG-104' 'PG-105','PG-110','PG-111','PG-112','PG-116', 'PG-117','PG-118'
Q_{ij}	68	'QF 1-2','QF 3-5','QF 5-6','QF 6-7','QF 9-10', 'QF 4-11','QF 5-11','QF 2-12','QF 7-12', 'QF 12-14','QF 14-15','QF 17-18','QF 21-22' 'QF 23-24','QF 28-29','QF 30-17','QF 17-31' 'QF 23-32','QF 34-36','QF 37-40','QF 39-40' 'QF 40-41','QF 43-44','QF 34-43','QF 46-48' 'QF 45-49','QF 52-53','QF 54-55','QF 56-57' 'QF 50-57','QF 51-58','QF 59-60','QF 60-62' 'QF 64-65','QF 62-67','QF 65-68','QF 47-69' 'QF 71-72','QF 71-73','QF 69-75','QF 74-75' 'QF 76-77','QF 78-79','QF 81-80','QF 77-82' 'QF 84-85','QF 86-87','QF 85-88','QF 91-92' 'QF 92-93','QF 94-95','QF 82-96','QF 92-100' 'QF 95-96','QF 98-100','QF 99-100','QF 100-101' 'QF 101-102','QF 100-106','QF 105-108', 'QF 108-109','QF 109-110','QF 17-113', 'QF 27-115','QF 114-115','QF 12-117','QF 75-118' 'QF 76-118'
Q_{ji}	66	'QT 11-12','QT 11-13','QT 13-15','QT 15-17', 'QT 18-19','QT 20-21','QT 21-22','QT 22-23', 'QT 23-25','QT 26-25','QT 27-28','QT 8-30', 'QT 29-31','QT 19-34','QT 35-37','QT 33-37' 'QT 30-38','QT 40-42','QT 41-42','QT 46-47' 'QT 42-49','QT 42-49','QT 48-49','QT 49-50' 'QT 49-51','QT 51-52','QT 49-54','QT 54-56' 'QT 55-56','QT 56-58','QT 54-59','QT 56-59' 'QT 59-61','QT 60-61','QT 63-59','QT 63-64' 'QT 49-66','QT 62-66','QT 65-66','QT 66-67' 'QT 49-69','QT 68-69','QT 24-70','QT 24-72' 'QT 70-74','QT 69-77','QT 75-77','QT 79-80'

		'QT 82-83','QT 85-86','QT 86-87','QT 88-89' 'QT 89-90','QT 92-94','QT 94-96','QT 80-98' 'QT 94-100','QT 96-97','QT 100-103','QT 104-105' 'QT 105-105','QT 106-107','QT 108-109', 'QT 32-113','QT 32-114','QT 68-116',
Q_{inj}	56	'QG-3','QG-4','QG-8','QG-9','QG-12','QG-13' 'QG-15','QG-16','QG-19','QG-20','QG-24','QG-25' 'QG-30','QG-31','QG-33','QG-35','QG-36','QG-38' 'QG-42','QG-44','QG-46','QG-47','QG-49','QG-52' 'QG-53','QG-54','QG-55','QG-61','QG-63','QG-64' 'QG-66','QG-68','QG-70','QG-71','QG-77','QG-79' 'QG-81','QG-83','QG-85','QG-86','QG-89','QG-90' 'QG-92','QG-96','QG-97','QG-98','QG-99','QG-102' 'QG-104,'QG-105','QG-110','QG-111', 'QG-112','QG-116','QG-117','QG-118'
V_i	61	'Vm-2','Vm-3','Vm-4','Vm-5','Vm-9','Vm-12' 'Vm-15','Vm-17','Vm-18','Vm-21','Vm-23','Vm-24' 'Vm-25','Vm-27','Vm-28','Vm-29','Vm-30','Vm-34' 'Vm-36','Vm-37','Vm-40','Vm-42','Vm-44','Vm-45' 'Vm-46','Vm-49','Vm-51','Vm-53','Vm-54','Vm-56' 'Vm-57','Vm-59','Vm-62','Vm-63','Vm-64','Vm-68' 'Vm-69','Vm-70','Vm-71','Vm-73','Vm-75','Vm-76' 'Vm-77','Vm-80','Vm-82','Vm-85','Vm-86','Vm-91' 'Vm-92','Vm-94','Vm-100','Vm-101','Vm-102', 'Vm-103','Vm-105','Vm-107','Vm-110', 'Vm-111','Vm-112','Vm-113','Vm-114'

5.4.1 White Noise

For IEEE 118 bus system, the white noise has been simulated into actual load flow values using equation 3.1. The estimation results with only white noise are shown in Figure 5.13 and summarized in Table 5.19.

The locations for votlatge magnitude meter are selected heuristically and shown in Table 5.18 for IEEE 118 bus system. The rest of voltge magnitude meters located at other bus have not been inlcuded in the test case as those locations are resulting higher CEE indicator. The second reason is to reduce the global redundancy of the test case because all the locations of a particalur power system are not connected with meters in parctice.

As described earlier, only two PMUs are considered to be placed in the system for this thesis. The first one is kept fixed at slack bus and the second one has considered to be relocated at different bus locations based on the number of connections that bus is having with other buses. The buses with only larger number of connnections are considered for second PMU installation

It has been observed from IEEE 14 and 30 bus results that the LMR estimator has lowest CEE indicator value without any PMU installation. The LMR estimator has also gained the lowest indicator value for white noise case in IEEE 118 bus system. The WLAV has highest indicator value which previously attained by the WLS. When PMU-5 is installed into the system, the CEE indicators for all algorithms has improved. It can also be observed that at PMU-37, all the algorithms have lowest indicator values when compared with their own

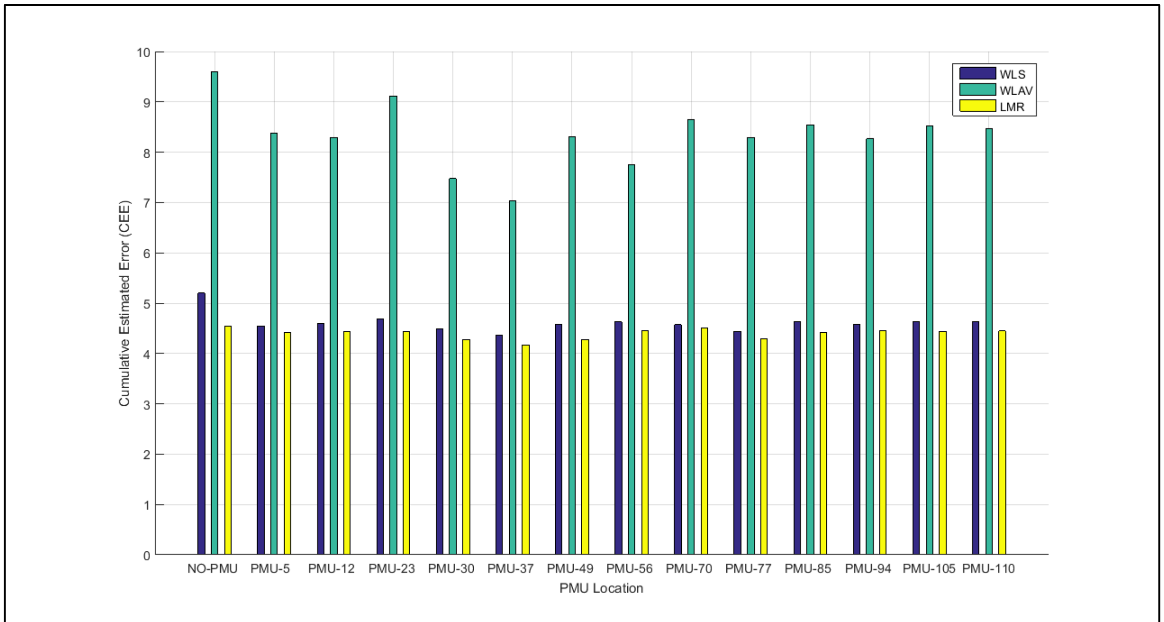

Figure 5.13 IEEE 118 Bus – White Noise

indicator values at other locations. But LMR estimator has best performance at all locations with zero rejections.

Table 5.19 IEEE 118 Bus – White Noise

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	5.201588291	9.602582807	4.540752623	0.001
	AOR	0	0	0	
PMU-5	Indicator	4.547691827	8.382100872	4.423316798	0.00051
	AOR	0	0	0	
PMU-12	Indicator	4.592511779	8.28771915	4.440882323	0.00019
	AOR	0	0	0	
PMU-23	Indicator	4.679206444	9.111990917	4.434697126	0.00068
	AOR	0	0	0	
PMU-30	Indicator	4.486572856	7.475416632	4.275605046	0.00027
	AOR	0	0	0	
PMU-37	Indicator	4.364822502	7.032760116	4.17554755	0.00053
	AOR	0	0	0	
PMU-49	Indicator	4.576190986	8.30133977	4.280977342	0.00041
	AOR	0	0	0	
PMU-56	Indicator	4.628540905	7.75633628	4.458124478	0.00053
	AOR	0	0	0	
PMU-70	Indicator	4.572216615	8.650374296	4.49912799	0.00021
	AOR	0	0	0	
PMU-77	Indicator	4.437857188	8.296956605	4.286647067	0.00046
	AOR	0	0	0	
PMU-85	Indicator	4.63138631	8.542195417	4.419821857	0.00038
	AOR	0	0	0	
PMU-94	Indicator	4.574672133	8.267325498	4.454717139	0.00033
	AOR	0	0	0	
PMU-105	Indicator	4.639449289	8.522700098	4.435641915	0.00059
	AOR	0	0	0	
PMU-110	Indicator	4.637821868	8.472135866	4.447769743	0.00032
	AOR	0	0	0	

5.4.2 Single Bad-Data as Power Flow Meter

In this case, a single Bad-Data as real power flow meter has been simulated on transmission

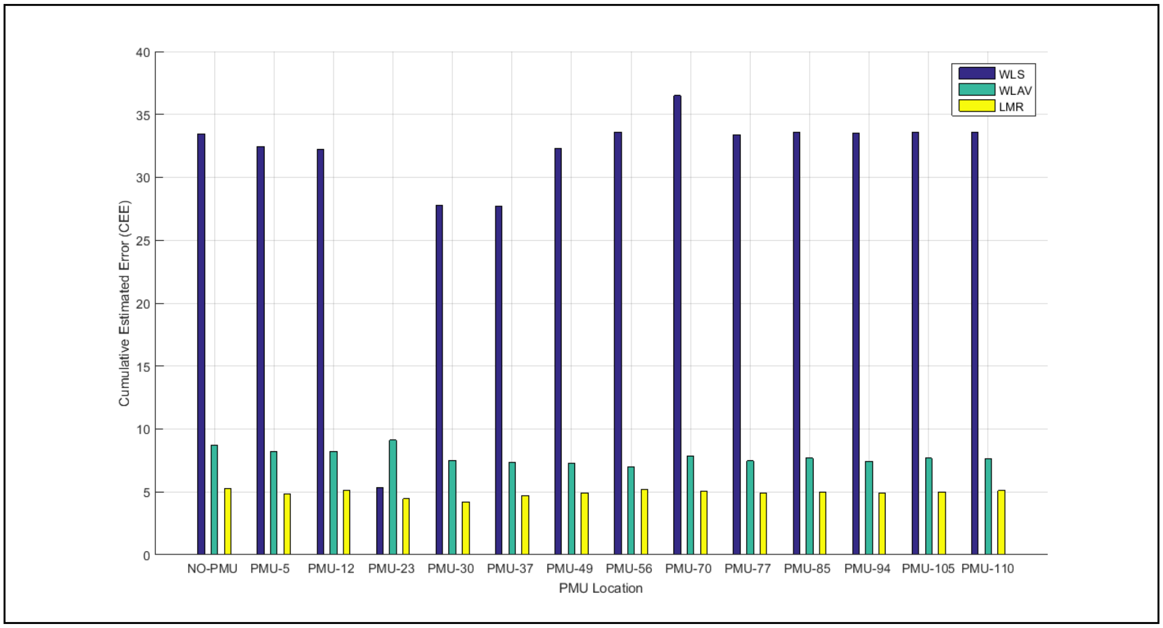

Figure 5.14 IEEE 118 Bus – Single Bad-Data as Power Flow Meter

line between bus 23 and 32. The simulation results are shown in Figure 5.14 and summarized in Table 5.20. The LMR estimator has lowest CEE indicator without any PMU into the system. But the WLS estimator failed to provide good estimation and its CEE indicator is very high. When PMU-23 is installed into the system, this high value of CEE indicator for WLS has dropped and it is near to the indicator value of LMR estimator. At PMU-23 the indicator value of WLAV has increased a little. While LMR estimator has best indicator values for all PMU locations with zero rejections.

Table 5.20 IEEE 118 Bus – Single Bad-Data as Power Flow Meter

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	33.45485729	8.73899759	5.246635831	0.001
	AOR	8	0	0	
PMU-5	Indicator	32.46172002	8.19467145	4.805007395	0.00051
	AOR	6	0	0	

PMU-12	Indicator	32.2362289	8.21530015	5.147548762	0.00019
	AOR	6	0	0	
PMU-23	Indicator	5.355121178	9.11199092	4.446862476	0.00068
	AOR	0	0	0	
PMU-30	Indicator	27.80207495	7.50488616	4.201110429	0.00027
	AOR	7	0	0	
PMU-37	Indicator	27.67659634	7.31402356	4.698343701	0.00053
	AOR	6	0	0	
PMU-49	Indicator	32.32400648	7.29327547	4.937015699	0.00041
	AOR	6	0	0	
PMU-56	Indicator	33.58224589	6.97905004	5.170510751	0.00053
	AOR	7	0	0	
PMU-70	Indicator	36.50741018	7.85290088	5.050904561	0.00021
	AOR	6	0	0	
PMU-77	Indicator	33.39883248	7.46320648	4.941869145	0.00046
	AOR	7	0	0	
PMU-85	Indicator	33.59024453	7.69148968	5.005956878	0.00038
	AOR	7	0	0	
PMU-94	Indicator	33.53230181	7.41661976	4.899247338	0.00033
	AOR	7	0	0	
PMU-105	Indicator	33.5972876	7.67199436	5.017893234	0.00059
	AOR	7	0	0	
PMU-110	Indicator	33.59568463	7.62143013	5.109250194	0.00032
	AOR	7	0	0	

5.4.3 Single Bad-Data as Power Injection Meter

Real power injection meter on bus 66 has been simulated as Bad-Data and it has been

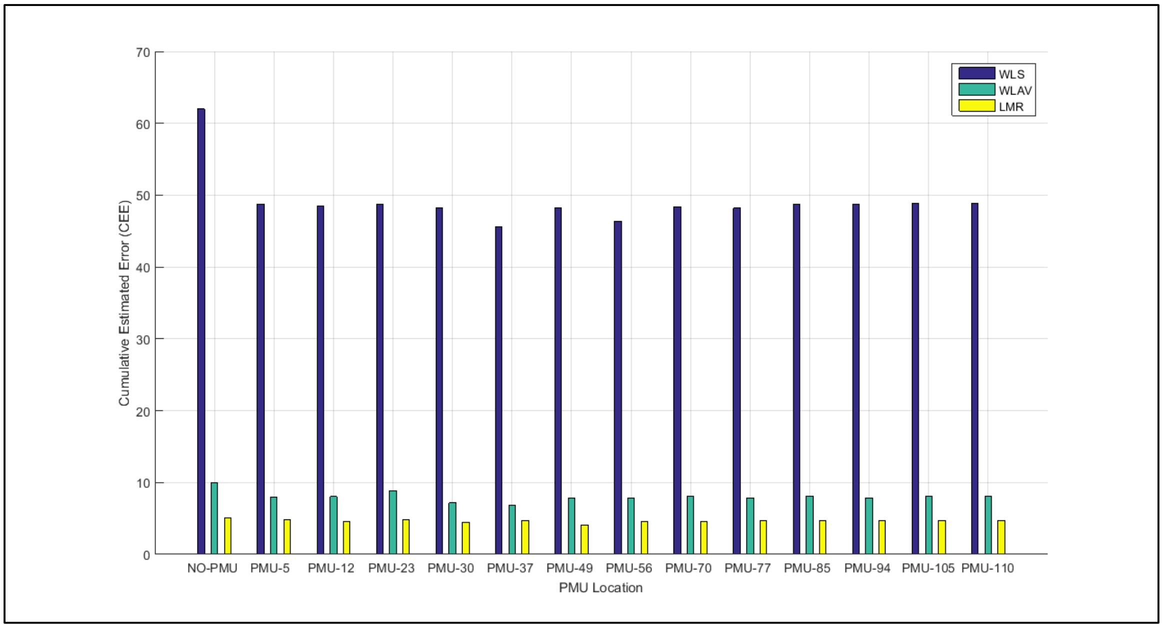

Figure 5.15 IEEE 118 Bus – Single Bad-Data as Power Injection Meter

assumed that terminal polarity of the meter has been reversed. This polarity inversion is considered as one of the worst Bad-Data. The CEE indicator results are plotted in Figure 5.15 and summarized in Table 5.21. The WLS has highest CEE indicator value and the LMR estimator has lowest indicator value without any PMU. When PMU-5 is installed into the system, the indicator has improved for all estimator. The indicator for the LMR estimator is lowest even with PMU-5. This can be seen from Figure 5.15 that there is improvement in the indicator value of WLS at all locations when compared with its own indicator values. But overall LMR estimator has lowest indicator values.

Table 5.21 IEEE 118 Bus – Single Bad-Data as Power Injection Meter

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	62.00888611	9.971602412	5.099281028	0.001
	AOR	22	1	1	
PMU-5	Indicator	48.75421672	7.95803001	4.803789442	0.00051

	AOR	15	0	0	
PMU-12	Indicator	48.45062134	8.031532693	4.611364251	0.00019
	AOR	15	0	0	
PMU-23	Indicator	48.79347646	8.833595023	4.876869351	0.00068
	AOR	15	0	0	
PMU-30	Indicator	48.24884665	7.181968427	4.494917446	0.00027
	AOR	15	0	0	
PMU-37	Indicator	45.53936864	6.827522488	4.725649176	0.00053
	AOR	14	0	0	
PMU-49	Indicator	48.24299201	7.864938718	4.130245914	0.00041
	AOR	23	0	0	
PMU-56	Indicator	46.34912022	7.875386541	4.607101661	0.00053
	AOR	13	0	0	
PMU-70	Indicator	48.36258472	8.103862833	4.625183384	0.00021
	AOR	15	0	0	
PMU-77	Indicator	48.21961984	7.877674074	4.645561625	0.00046
	AOR	14	0	0	
PMU-85	Indicator	48.78822724	8.107532779	4.73996913	0.00038
	AOR	15	0	1	
PMU-94	Indicator	48.73714047	7.832662859	4.66589802	0.00033
	AOR	15	0	1	
PMU-105	Indicator	48.80572636	8.088037459	4.76575465	0.00059
	AOR	15	0	1	
PMU-110	Indicator	48.80565328	8.037473229	4.740988317	0.00032
	AOR	15	0	0	

5.4.4 Single Bad-Data as Voltage Magnitude Meter

A single Bad-Data as voltage magnitude meter on bus 36 has been simulated with 5σ increase in actual load flow value. The results are shown in Figure 5.16 and summarized in Table 5.22. It can be observed that the CEE indicator value of WLS has middle position throughout the plot which was highest in the previous two cases. The LMR estimator is still giving good estimation results and its CEE indicator value is lowest. For PMU-37, the WLS and WLAV has lowest indicator values when compared with its own indicator value. The LMR estimator has overall best performance indicator.

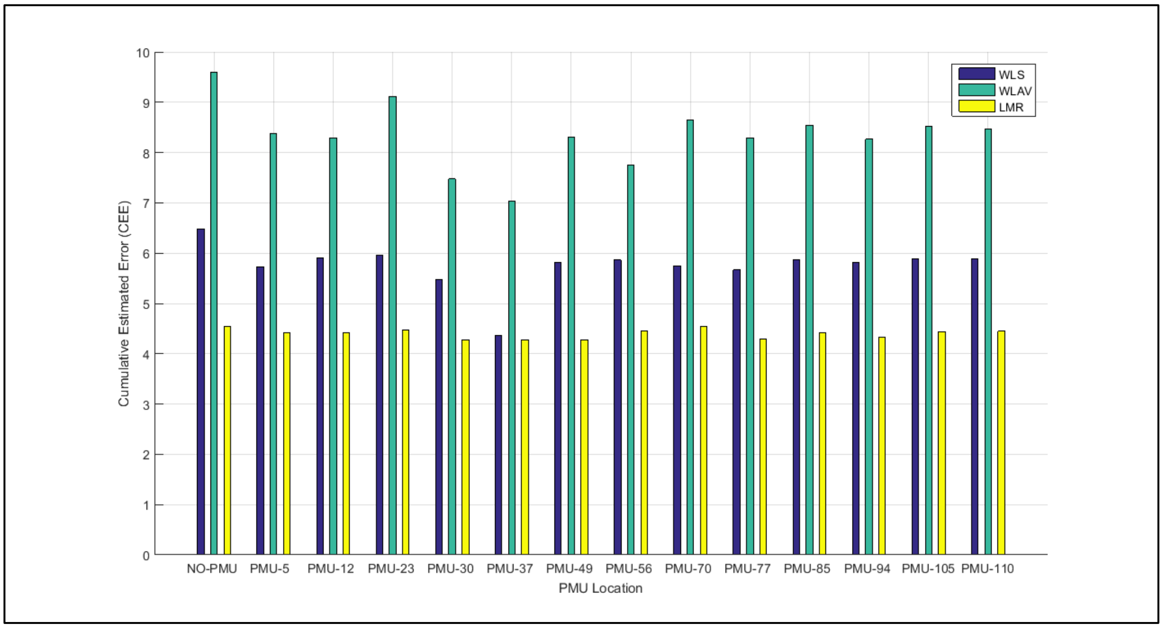

Figure 5.16 IEEE 118 Bus – Single Bad-Data as Voltage Magnitude Meter

Table 5.22 IEEE 118 Bus – Single Bad-Data as Voltage Magnitude Meter

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	6.48554206	9.602582805	4.540752623	0.001
	AOR	0	0	0	
PMU-5	Indicator	5.729448079	8.382100872	4.4255047	0.00051
	AOR	0	0	0	
PMU-12	Indicator	5.912387165	8.28771915	4.41092106	0.00019
	AOR	0	0	0	
PMU-23	Indicator	5.964368356	9.111990917	4.468739065	0.00068
	AOR	0	0	0	
PMU-30	Indicator	5.476673303	7.475416632	4.275153659	0.00027
	AOR	0	0	0	
PMU-37	Indicator	4.369462751	7.032760116	4.276713973	0.00053
	AOR	0	0	0	
PMU-49	Indicator	5.820619775	8.301339488	4.280976725	0.00041
	AOR	0	0	0	
PMU-56	Indicator	5.867574871	7.75633628	4.458124581	0.00053
	AOR	0	0	0	
PMU-70	Indicator	5.747676584	8.650374296	4.540340413	0.00021
	AOR	0	0	0	
PMU-77	Indicator	5.667863584	8.296956605	4.284459036	0.00046
	AOR	0	0	0	
PMU-85	Indicator	5.877055791	8.542195417	4.419949746	0.00038
	AOR	0	0	0	

PMU-94	Indicator	5.82129125	8.267325498	4.335270781	0.00033
	AOR	0	0	0	
PMU-105	Indicator	5.885759093	8.522700098	4.434244167	0.00059
	AOR	0	0	0	
PMU-110	Indicator	5.884087026	8.472135867	4.449956211	0.00032
	AOR	0	0	0	

5.4.5 Multiple Non-Interacting Bad-Data

The sensitivity matrix has been used to select multiple non-interacting measurements. This combination consists of the power flow meter between bus 4 and 11, the real power injection meter on bus 16 and voltage magnitude meter on bus 3. These measurements have been simulated as Bad-Data. The simulation results for multiple non-interacting are shown

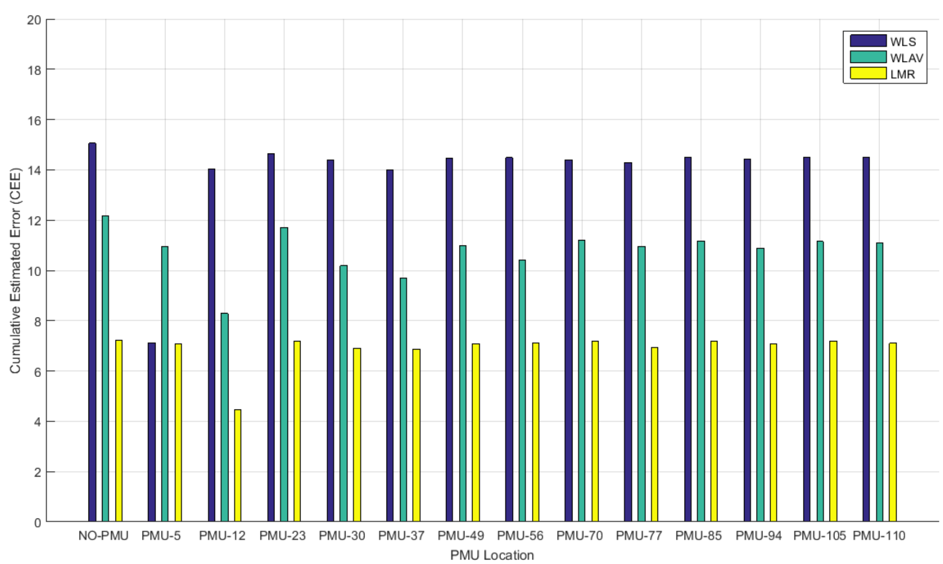

Figure 5.17 IEEE 118 Bus – Multiple Non-Interacting Bad-Data

in Figure 5.17 and summarized in Table 5.23. Without any PMU installed, the WLS has the highest indicator value and the LMR estimator has the lowest CEE value. But after PMU-5 installation, the CEE indicator for WLS has improved and it is close to the indicator for LMR estimator. But this was the only PMU location where the WLS has lowest indicator when compared with its own indicator values. At PMU-12, the indicator values for LMR and WLAV has lowest values in comparison with their own indicators. From the 18, it can be observed that LMR estimator has overall best indicator values for all PMU locations.

Table 5.23 IEEE 118 Bus – Multiple Non-Interacting Bad-Data

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	15.05627701	12.1618692	7.230949925	0.001
	AOR	5	2	2	
PMU-5	Indicator	7.118756482	10.9495762	7.061263667	0.00051
	AOR	1	1	1	
PMU-12	Indicator	14.03111495	8.28885564	4.477436238	0.00019
	AOR	4	0	0	
PMU-23	Indicator	14.64449377	11.7182134	7.178085941	0.00068
	AOR	5	1	2	
PMU-30	Indicator	14.4035327	10.1932101	6.906977687	0.00027
	AOR	5	1	2	
PMU-37	Indicator	14.00153776	9.69489701	6.862667898	0.00053
	AOR	5	1	2	
PMU-49	Indicator	14.46088059	10.9698457	7.095178976	0.00041
	AOR	5	1	2	
PMU-56	Indicator	14.48176558	10.4168108	7.115720864	0.00053
	AOR	5	1	2	
PMU-70	Indicator	14.39006318	11.1907387	7.180749347	0.00021
	AOR	5	1	2	
PMU-77	Indicator	14.28286729	10.9578178	6.948920631	0.00046
	AOR	5	1	2	
PMU-85	Indicator	14.48705706	11.167652	7.176320875	0.00038
	AOR	5	1	2	
PMU-94	Indicator	14.4299488	10.8927821	7.090538728	0.00033
	AOR	5	1	2	
PMU-105	Indicator	14.49482399	11.1481567	7.196676439	0.00059
	AOR	5	1	2	
PMU-110	Indicator	14.49320897	11.0975925	7.11006894	0.00032
	AOR	5	1	2	

5.4.6 Multiple Interacting Bad-Data

The last case is multiple interacting Bad-Data where the real power flow meter between bus 34 and 36, the real power injection meter on bus 33 and the voltage magnitude meter on bus 18 have been chosen as interacting meters and simulated as Bad-Data. This information is carefully selected from the sensitivity matrix. The results are plotted in Figure 5.18 and summarized in Table 5.24. Like all other cases, LMR estimator has

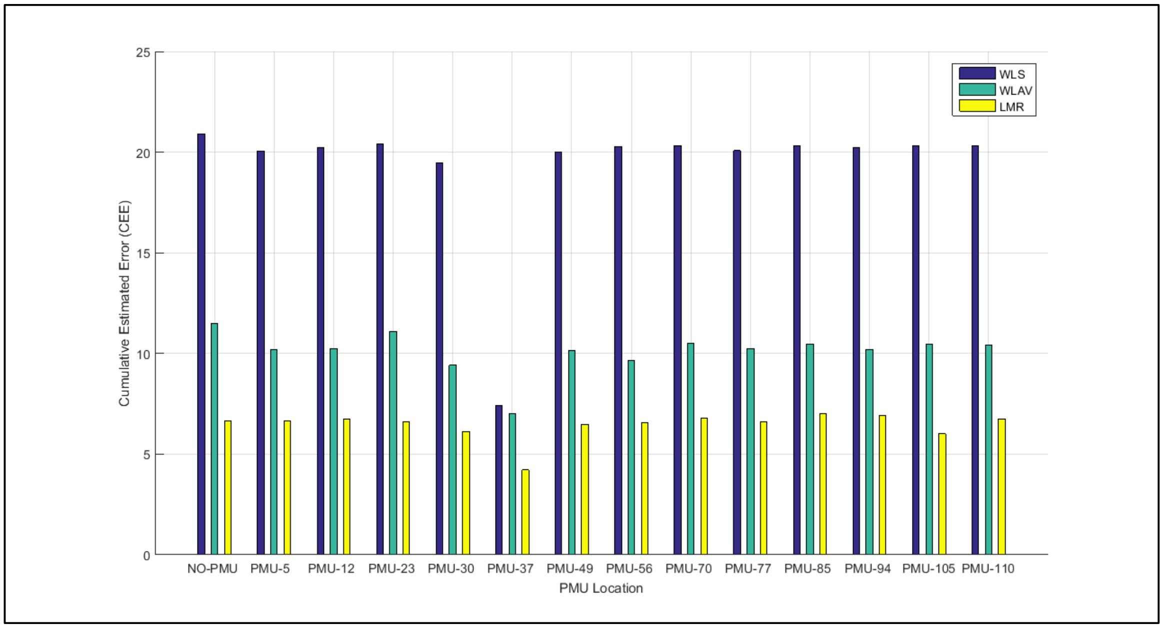

Figure 5.18 IEEE 118 Bus – Multiple Interacting Bad-Data

produced best results for the state estimation. The PMU-37 has shown a lowest indicator values of each algorithms. The LMR estimator has lowest CEE indicator value at all location in comparison with other estimators and the WLS has highest indicator value when compared with other algorithms.

Table 5.24 IEEE 118 Bus – Multiple Interacting Bad-Data

		WLS	WLAV	LMR	LMR Tolerance
NO PMU	Indicator	20.89571959	11.48354153	6.672585665	0.001
	AOR	4	3	3	

PMU-5	Indicator	20.06939699	10.21344103	6.673809113	0.00051
	AOR	4	3	3	
PMU-12	Indicator	20.21692355	10.23810937	6.72960681	0.00019
	AOR	4	3	3	
PMU-23	Indicator	20.3855606	11.0927144	6.619390906	0.00068
	AOR	4	3	3	
PMU-30	Indicator	19.44840281	9.423992969	6.137627679	0.00027
	AOR	4	3	3	
PMU-37	Indicator	7.394724834	7.007518132	4.225703078	0.00053
	AOR	0	0	0	
PMU-49	Indicator	19.99744825	10.15601911	6.486736964	0.00041
	AOR	4	3	2	
PMU-56	Indicator	20.29237741	9.656719447	6.557176651	0.00053
	AOR	4	3	2	
PMU-70	Indicator	20.31433326	10.50053556	6.775499163	0.00021
	AOR	4	3	2	
PMU-77	Indicator	20.077893	10.25115598	6.59511571	0.00046
	AOR	4	3	2	
PMU-85	Indicator	20.30087796	10.4810617	7.021137177	0.00038
	AOR	4	3	2	
PMU-94	Indicator	20.24472895	10.20619178	6.937518897	0.00033
	AOR	4	3	2	
PMU-105	Indicator	20.30911849	10.46156638	6.01503439	0.00059
	AOR	4	3	1	
PMU-110	Indicator	20.30736739	10.41100215	6.75353548	0.00032
	AOR	4	3	2	

5.4.7 Results Discussion on IEEE 118 Bus

The inclusion of voltage and current phasors could improve the accuracy of estimator if proper location of PMU is selected. Without any PMU, the LMR estimator has lowest CEE indicator for all cases among the other estimators. With PMU installation, the LMR estimator has improved the accuracy of the estimated variables in all cases. The indicator value for WLS is very high in the presence of single Bad-Data as power flow and power injection meter. But there is improvement in CEE indicator for all algorithms in most cases.

The CEE indicator for the LMR estimator has shown it as best robust estimator in comparison with the WLS and WLAV.

5.5 Overall Discussion of Results

This chapter summarizes all the results for IEEE 14, IEEE 30 and IEEE 118 bus system test cases with different Bad-Data scenarios. Details of the results are plotted in Figures (5.1 to 5.18) and presented in the Tables (5.5 to 5.24) for clear understanding. The inclusion of voltage and current phasors could improve the accuracy of estimator if proper location of PMU is selected. It is a clear observation that without any PMU, the LMR estimator has lowest CEE indicator for all cases among the other estimators. With PMU installation, the LMR estimator has improved the accuracy of the estimated variables in all cases. The CEE indicator for WLS and WLAV have also improved after PMU installation but could not get closer to LMR estimator for most of the cases. The overall performance for LMR estimator is best in all the scenarios irrespective of the Bad-Data presence and test case size. The state estimation results are system dependent and it depends on meter configuration, standard deviation of meters and network topology of the system.

CHAPTER 6

CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

In the thesis, the use of LMR estimator in the presence of PMU voltage and current phasors coming from different locations is investigated and it has been clearly reflected that the accuracy of the state estimation has been improved significantly. The overall performance for LMR estimator when compared with WLS and WLAV has been found best irrespective of the Bad-Data presence and test case size. Besides of the single Bad-Data cases, multiple interacting and non-interacting bad-data cases were investigated which clearly reflected the robustness of LMR estimator. The working principle of LMR estimator depends upon proper tolerance level and rejection of unreliable measurement values, which has already been explained in the section 4.1.3. In this thesis, the tolerance value of LMR estimator is tuned iteratively and the best value of tolerance for each of test case has been proposed. The accurate meter readings from PMUs can be easily incorporated into WLS or WLAV by using error covariance matrix. But for LMR estimator, it was not possible to apply such higher weights to PMU meter readings like WLS. From simulation and analysis, it has been found that the tolerance should be zero for all PMU meter readings. The accuracy of the estimator also depends upon the proper selection of the buses where the new PMUs are to be installed. This issue is carefully addressed in the thesis for all test cases of IEEE 14, IEEE 30 and IEEE 118 bus system.

Algorithm's development and modification is carried out at MATLAB platform in MATPOWER package. The proposed approach has been successfully tested on IEEE 14, IEEE 30 and IEEE 118 bus system with different Bad-Data scenarios and the results show the improvement in CEE indicator with PMU inclusion into the system.

6.2 Future Works

There is need to find out the exact value or mechanism for tolerance parameter of LMR estimator, either for every meter or for the whole system. From this thesis, it can be suggested that tolerance should be different for every meter installed in a power system and it can be somehow related with meter calibration, life, environmental conditions, and accuracy. If this issue can be addressed properly then LMR estimator can be one of the best robust state estimator. Currently, most of the PMU placement optimization function includes cost constraints but if CEE indicator can also be incorporated into optimization function then it will not only ensure observability of the system but also a better estimation results can be obtained.

APPENDIX A

IEEE SYSTEMS RAW DATA

A.1. IEEE 14 Bus System Data

A.1.1. Single Line Diagram

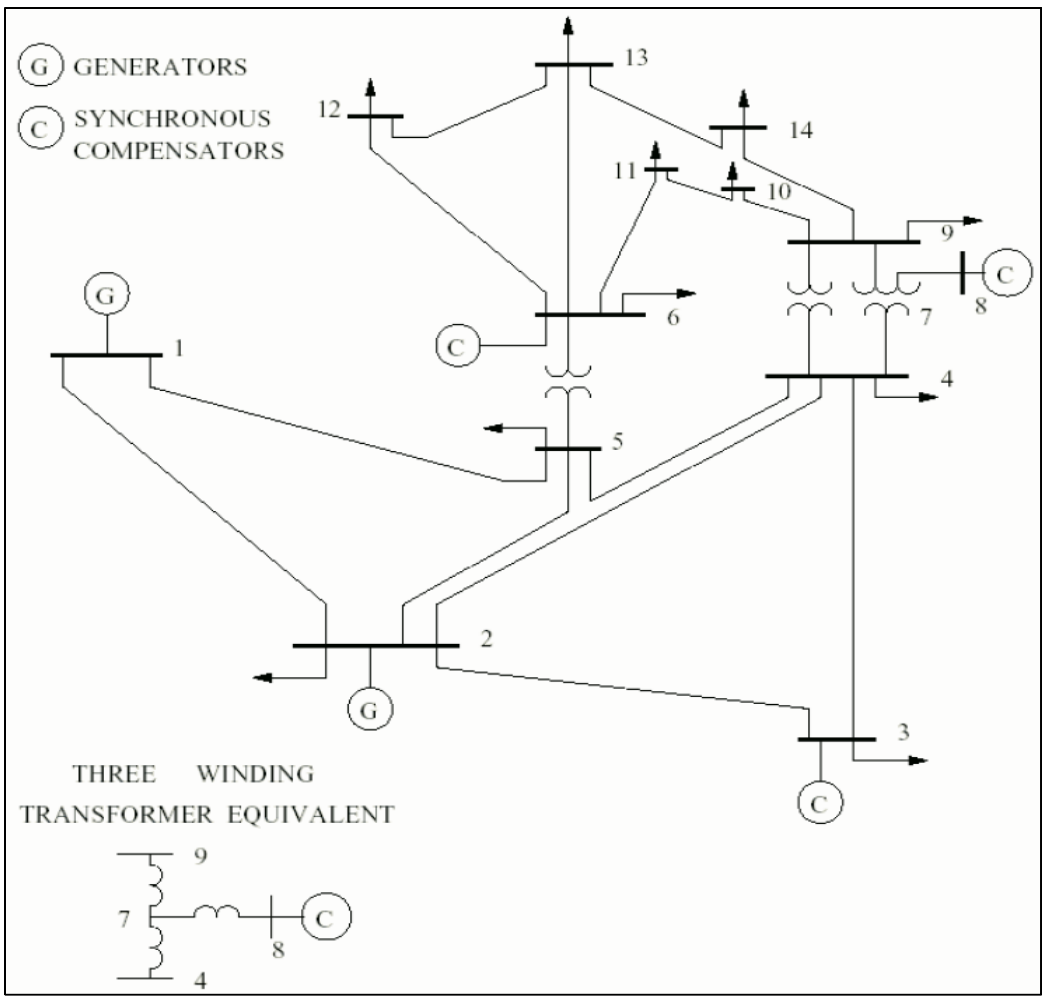

Figure A.1 IEEE 14 Bus System – Single Line Diagram [46]

A.1.2. Line Data

Table A.1 IEEE 14 Bus System – Line Data

From Bus	To Bus	R	X	B	Tap Setting
1	2	0.01938	0.05917	0.0528	0
1	5	0.05403	0.22304	0.0492	0
2	3	0.04699	0.19797	0.0438	0
2	4	0.05811	0.17632	0.034	0
2	5	0.05695	0.17388	0.0346	0
3	4	0.06701	0.17103	0.0128	0
4	5	0.01335	0.04211	0	0
4	7	0	0.20912	0	0.978
4	9	0	0.55618	0	0.969
5	6	0	0.25202	0	0.932
6	11	0.09498	0.1989	0	0
6	12	0.12291	0.25581	0	0
6	13	0.06615	0.13027	0	0
7	8	0	0.17615	0	0
7	9	0	0.11001	0	0
9	10	0.03181	0.0845	0	0
9	14	0.12711	0.27038	0	0
10	11	0.08205	0.19207	0	0
12	13	0.22092	0.19988	0	0
13	14	0.17093	0.34802	0	0

A.1.3. Bus Data

Table A.2 IEEE 14 Bus System – Bus Data

Sr	Bus Type	|V|	Generation		Load		Generation Limits	
			MW	MAVR	MW	MAVR	Max	Min
1	3	1.06	232.39	-16.549	0	0	0	0
2	2	1.045	40	43.55	21.7	12.7	50	-40
3	2	1.01	0	25.07	94.2	19	40	0
4	1	1.018	0	0	47.8	-3.9	-	-
5	1	1.02	0	0	7.6	1.6	-	-
6	2	1.07	0	12.73	11.2	7.5	24	-6
7	1	1.062	0	0	0	0	-	-
8	2	1.09	0	17.62	0	0	24	-6
9	1	1.056	0	0	29.5	16.6	-	-
10	1	1.051	0	0	9	5.8	-	-
11	1	1.057	0	0	3.5	1.8	-	-

12	1	1.055	0	0	6.1	1.6	-	-
13	1	1.05	0	0	13.5	5.8	-	-
14	1	1.036	0	0	14.9	5	-	-

A.1.4. Load Flow Data and Simulated Measurements

Table A.3 IEEE 14 Bus System – Load Flow Data and Simulated Measurements

Type	Index	Actual	Measurement	Type	Index	Actual	Measurement
V1	1	1.06E+00	1.06E+00	P13-14	20	5.64E-02	5.56E-02
V2	2	1.05E+00	1.05E+00	P2-1	1	-1.53E+00	-1.54E+00
V3	3	1.01E+00	1.01E+00	P5-1	2	-7.27E-01	-7.40E-01
V4	4	1.02E+00	1.02E+00	P3-2	3	-7.09E-01	-7.20E-01
V5	5	1.02E+00	1.02E+00	P4-2	4	-5.45E-01	-5.34E-01
V6	6	1.07E+00	1.08E+00	P5-2	5	-4.06E-01	-3.99E-01
V7	7	1.06E+00	1.07E+00	P4-3	6	2.37E-01	2.37E-01
V8	8	1.09E+00	1.08E+00	P5-4	7	6.17E-01	6.18E-01
V9	9	1.06E+00	1.07E+00	P7-4	8	-2.81E-01	-2.78E-01
V10	10	1.05E+00	1.06E+00	P9-4	9	-1.61E-01	-1.60E-01
V11	11	1.06E+00	1.06E+00	P6-5	10	-4.41E-01	-4.36E-01
V12	12	1.06E+00	1.06E+00	P11-6	11	-7.30E-02	-7.34E-02
V13	13	1.05E+00	1.06E+00	P12-6	12	-7.71E-02	-7.72E-02
V14	14	1.04E+00	1.04E+00	P13-6	13	-1.75E-01	-1.79E-01
P1	1	2.32E+00	2.34E+00	P8-7	14	0.00E+00	0.00E+00
P2	2	1.83E-01	1.86E-01	P9-7	15	-2.81E-01	-2.86E-01
P3	3	-9.42E-01	-9.61E-01	P10-9	16	-5.21E-02	-5.18E-02
P4	4	-4.78E-01	-4.72E-01	P14-9	17	-9.31E-02	-9.18E-02
P5	5	-7.60E-02	-7.49E-02	P11-10	18	3.80E-02	3.86E-02
P6	6	-1.12E-01	-1.13E-01	P13-12	19	-1.61E-02	-1.59E-02
P7	7	0.00E+00	0.00E+00	P14-13	20	-5.59E-02	-5.64E-02
P8	8	0.00E+00	0.00E+00	Q1-2	1	-2.04E-01	-2.06E-01
P9	9	-2.95E-01	-2.98E-01	Q1-5	2	3.86E-02	3.81E-02
P10	10	-9.00E-02	-8.92E-02	Q2-3	3	3.56E-02	3.49E-02
P11	11	-3.50E-02	-3.49E-02	Q2-4	4	-1.55E-02	-1.59E-02
P12	12	-6.10E-02	-6.01E-02	Q2-5	5	1.17E-02	1.21E-02
P13	13	-1.35E-01	-1.32E-01	Q3-4	6	4.47E-02	4.56E-02
P14	14	-1.49E-01	-1.51E-01	Q4-5	7	1.58E-01	1.53E-01
Q1	1	-1.65E-01	-1.65E-01	Q4-7	8	-9.68E-02	-9.78E-02
Q2	2	3.09E-01	3.07E-01	Q4-9	9	-4.28E-03	-4.28E-03
Q3	3	6.08E-02	6.00E-02	Q5-6	10	1.25E-01	1.25E-01
Q4	4	3.90E-02	3.87E-02	Q6-11	11	3.56E-02	3.53E-02
Q5	5	-1.60E-02	-1.55E-02	Q6-12	12	2.50E-02	2.45E-02
Q6	6	5.23E-02	5.37E-02	Q6-13	13	7.22E-02	7.28E-02
Q7	7	0.00E+00	0.00E+00	Q7-8	14	-1.72E-01	-1.66E-01
Q8	8	1.76E-01	1.81E-01	Q7-9	15	5.78E-02	5.64E-02
Q9	9	-1.66E-01	-1.61E-01	Q9-10	16	4.22E-02	4.37E-02

Q10	10	-5.80E-02	-5.83E-02	Q9-14	17	3.61E-02	3.72E-02
Q11	11	-1.80E-02	-1.77E-02	Q10-11	18	-1.62E-02	-1.57E-02
Q12	12	-1.60E-02	-1.59E-02	Q12-13	19	7.54E-03	7.54E-03
Q13	13	-5.80E-02	-5.75E-02	Q13-14	20	1.75E-02	1.81E-02
Q14	14	-5.00E-02	-5.05E-02	Q2-1	1	2.77E-01	2.82E-01
P1-2	1	1.57E+00	1.54E+00	Q5-1	2	2.23E-02	2.28E-02
P1-5	2	7.55E-01	7.57E-01	Q3-2	3	1.60E-02	1.60E-02
P2-3	3	7.32E-01	7.20E-01	Q4-2	4	3.02E-02	3.09E-02
P2-4	4	5.61E-01	5.56E-01	Q5-2	5	-2.10E-02	-2.18E-02
P2-5	5	4.15E-01	4.20E-01	Q4-3	6	-4.84E-02	-5.02E-02
P3-4	6	-2.33E-01	-2.34E-01	Q5-4	7	-1.42E-01	-1.44E-01
P4-5	7	-6.12E-01	-6.07E-01	Q7-4	8	1.14E-01	1.10E-01
P4-7	8	2.81E-01	2.81E-01	Q9-4	9	1.73E-02	1.74E-02
P4-9	9	1.61E-01	1.61E-01	Q6-5	10	-8.05E-02	-7.80E-02
P5-6	10	4.41E-01	4.33E-01	Q11-6	11	-3.44E-02	-3.42E-02
P6-11	11	7.35E-02	7.21E-02	Q12-6	12	-2.35E-02	-2.28E-02
P6-12	12	7.79E-02	7.78E-02	Q13-6	13	-6.80E-02	-7.02E-02
P6-13	13	1.77E-01	1.78E-01	Q8-7	14	1.76E-01	1.79E-01
P7-8	14	0.00E+00	0.00E+00	Q9-7	15	-4.98E-02	-5.07E-02
P7-9	15	2.81E-01	2.79E-01	Q10-9	16	-4.18E-02	-4.25E-02
P9-10	16	5.23E-02	5.27E-02	Q14-9	17	-3.36E-02	-3.33E-02
P9-14	17	9.43E-02	9.57E-02	Q11-10	18	1.64E-02	1.62E-02
P10-11	18	-3.79E-02	-3.80E-02	Q13-12	19	-7.48E-03	-7.58E-03
P12-13	19	1.61E-02	1.58E-02	Q14-13	20	-1.64E-02	-1.60E-02

A.1.5. Measurement Distribution for Test Case

Table A.4 IEEE 14 Bus System – Measurement Distribution for Test Case

Type	Index	Actual	Measurement	Type	Index	Actual	Measurement
V1	1	1.060E+00	1.060E+00	P7-8	14	0.000E+00	0.000E+00
V3	3	1.010E+00	1.010E+00	P9-14	17	9.426E-02	9.426E-02
V11	11	1.057E+00	1.057E+00	P12-13	19	1.614E-02	1.614E-02
V13	13	1.050E+00	1.050E+00	P13-14	20	5.644E-02	5.644E-02
P1	1	2.324E+00	2.324E+00	P2-1	1	-1.526E+00	-1.526E+00
P2	2	1.830E-01	1.830E-01	P3-2	3	-7.091E-01	-7.091E-01
P3	3	-9.420E-01	-9.420E-01	P5-4	7	6.167E-01	6.167E-01
P6	6	-1.120E-01	-1.120E-01	P8-7	14	0.000E+00	0.000E+00
P7	7	0.000E+00	0.000E+00	P11-6	11	-7.298E-02	-7.298E-02
P9	9	-2.950E-01	-2.950E-01	P13-12	19	-1.608E-02	-1.608E-02
P10	10	-9.000E-02	-9.000E-02	Q1-2	1	-2.040E-01	-2.040E-01
P12	12	-6.100E-02	-6.100E-02	Q1-5	2	3.855E-02	3.855E-02
P13	13	-1.350E-01	-1.350E-01	Q2-3	3	3.560E-02	3.560E-02
Q1	1	-1.655E-01	-1.655E-01	Q3-4	6	4.473E-02	4.473E-02
Q2	2	3.086E-01	3.086E-01	Q4-7	8	-9.681E-02	-9.681E-02

Q3	3	6.075E-02	6.075E-02	Q6-11	11	3.560E-02	3.560E-02
Q6	6	5.231E-02	5.231E-02	Q6-13	13	7.217E-02	7.217E-02
Q9	9	-1.660E-01	-1.660E-01	Q7-8	14	-1.716E-01	-1.716E-01
Q10	10	-5.800E-02	-5.800E-02	Q9-14	17	3.610E-02	3.610E-02
Q12	12	-1.600E-02	-1.600E-02	Q12-13	19	7.540E-03	7.540E-03
Q13	13	-5.800E-02	-5.800E-02	Q13-14	20	1.747E-02	1.747E-02
P1-2	1	1.569E+00	1.569E+00	Q2-1	1	2.768E-01	2.768E-01
P1-5	2	7.551E-01	7.551E-01	Q3-2	3	1.602E-02	1.602E-02
P2-3	3	7.324E-01	7.324E-01	Q5-4	7	-1.420E-01	-1.420E-01
P3-4	6	-2.329E-01	-2.329E-01	Q11-6	11	-3.445E-02	-3.445E-02
P4-7	8	2.807E-01	2.807E-01	Q8-7	14	1.762E-01	1.762E-01
P6-11	11	7.353E-02	7.353E-02	Q13-12	19	-7.483E-03	-7.483E-03
P6-13	13	1.775E-01	1.775E-01				

A.2. IEEE 30 Bus System Data

A.2.1. Single Line Diagram

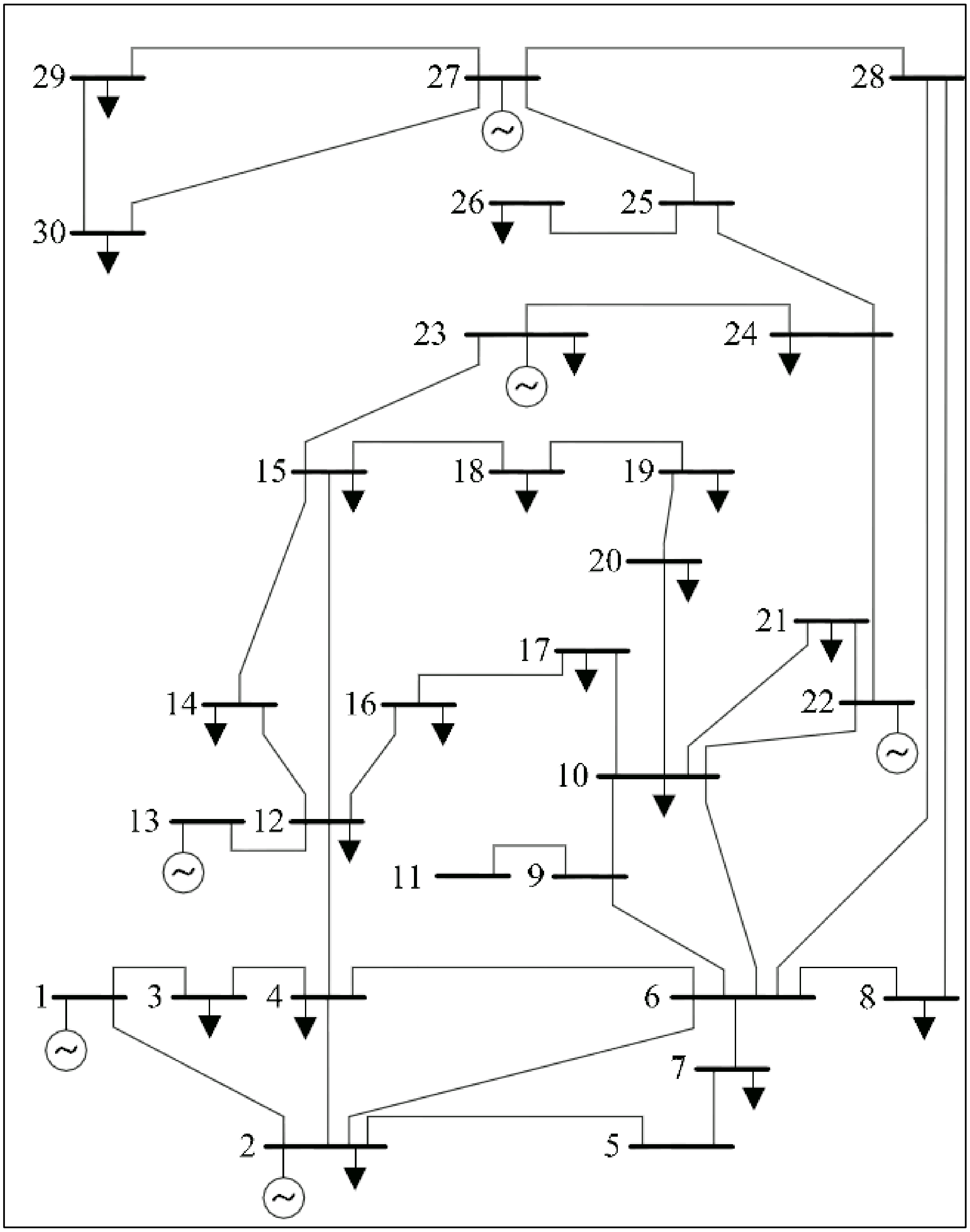

Figure A.2 IEEE 30 Bus System – Single Line Diagram [46]

A.2.2. Line Data

Table A.5 IEEE 30 Bus System – Line Data

From Bus	To Bus	R	X	B	Tap Setting
1	2	0.0192	0.0575	0.0528	0
1	3	0.0452	0.1652	0.0408	0
2	4	0.057	0.1737	0.0368	0
3	4	0.0132	0.0379	0.0084	0
2	5	0.0472	0.1983	0.0418	0
2	6	0.0581	0.1763	0.0374	0
4	6	0.0119	0.0414	0.009	0
5	7	0.046	0.116	0.0204	0
6	7	0.0267	0.082	0.017	0
6	8	0.012	0.042	0.009	0
6	9	0	0.208	0	0.978
6	10	0	0.556	0	0.969
9	11	0	0.208	0	0
9	10	0	0.11	0	0
4	12	0	0.256	0	0.932
12	13	0	0.14	0	0
12	14	0.1231	0.2559	0	0
12	15	0.0662	0.1304	0	0
12	16	0.0945	0.1987	0	0
14	15	0.221	0.1997	0	0
16	17	0.0524	0.1923	0	0
15	18	0.1073	0.2185	0	0
18	19	0.0639	0.1292	0	0
19	20	0.034	0.068	0	0
10	20	0.0936	0.209	0	0
10	17	0.0324	0.0845	0	0
10	21	0.0348	0.0749	0	0
10	22	0.0727	0.1499	0	0
21	22	0.0116	0.0236	0	0
15	23	0.1	0.202	0	0
22	24	0.115	0.179	0	0
23	24	0.132	0.27	0	0
24	25	0.1885	0.3292	0	0
25	26	0.2544	0.38	0	0
25	27	0.1093	0.2087	0	0
28	27	0	0.396	0	0.968
27	29	0.2198	0.4153	0	0
27	30	0.3202	0.6027	0	0
29	30	0.2399	0.4533	0	0
8	28	0.0636	0.2	0.0428	0
6	28	0.0169	0.0599	0.013	0

A.2.3. Bus Data

Table A.6 IEEE 30 Bus System – Bus Data

Sr	Bus Type	|V|	Generation		Load		Generation Limits	
			MW	MVAR	MW	MVAR	Max	Min
1	3	1.06	260.95	-20.41	0	0	10	0
2	2	1.043	40	56.06	21.7	12.7	50	-40
3	1	1.021	0	0	2.4	1.2	-	-
4	1	1.012	0	0	7.6	1.6	-	-
5	2	1.01	0	35.65	94.2	19	40	-40
6	1	1.01	0	0	0	0	-	-
7	1	1.002	0	0	22.8	10.9	-	-
8	2	1.01	0	36.11	30	30	40	-10
9	1	1.051	0	0	0	0	-	-
10	1	1.045	0	0	5.8	2	-	-
11	2	1.082	0	16.05	0	0	24	-6
12	1	1.057	0	0	11.2	7.5	-	-
13	2	1.071	0	10.45	0	0	0	10.45
14	1	1.042	0	0	6.2	1.6	-	-
15	1	1.038	0	0	8.2	2.5	-	-
16	1	1.045	0	0	3.5	1.8	-	-
17	1	1.04	0	0	9	5.8	-	-
18	1	1.028	0	0	3.2	0.9	-	-
19	1	1.026	0	0	9.5	3.4	-	-
20	1	1.03	0	0	2.2	0.7	-	-
21	1	1.033	0	0	17.5	11.2	-	-
22	1	1.033	0	0	0	0	-	-
23	1	1.027	0	0	3.2	1.6	-	-
24	1	1.021	0	0	8.7	6.7	-	-
25	1	1.017	0	0	0	0	-	-
26	1	1	0	0	3.5	2.3	-	-
27	1	1.023	0	0	0	0	-	-
28	1	1.007	0	0	0	0	-	-
29	1	1.003	0	0	2.4	0.9	-	-
30	1	0.992	0	0	10.6	1.9	-	-

A.2.4. Load Flow Data and Simulated Measurements

Table A.7 IEEE 30 Bus System – Load Flow Data and Simulated Measurements

Type	Index	Actual	Measurement	Type	Index	Actual	Measurement
Vm-1	1	1.06E+00	1.05E+00	PF 27-30	38	7.09E-02	7.22E-02
Vm-2	2	1.05E+00	1.04E+00	PF 29-30	39	3.70E-02	3.71E-02
Vm-3	3	1.02E+00	1.02E+00	PF 8-28	40	-5.45E-03	-5.40E-03

Vm-4	4	1.01E+00	1.01E+00	PF 6-28	41	1.87E-01	1.86E-01
Vm-5	5	1.01E+00	1.02E+00	PT 2-1	1	-1.68E+00	-1.65E+00
Vm-6	6	1.01E+00	1.01E+00	PT 3-1	2	-8.45E-01	-8.42E-01
Vm-7	7	1.00E+00	1.00E+00	PT 4-2	3	-4.26E-01	-4.18E-01
Vm-8	8	1.01E+00	1.00E+00	PT 4-3	4	-8.13E-01	-8.01E-01
Vm-9	9	1.05E+00	1.05E+00	PT 5-2	5	-7.94E-01	-8.03E-01
Vm-10	10	1.05E+00	1.05E+00	PT 6-2	6	-5.84E-01	-5.80E-01
Vm-11	11	1.08E+00	1.08E+00	PT 6-4	7	-7.15E-01	-7.03E-01
Vm-12	12	1.06E+00	1.06E+00	PT 7-5	8	1.50E-01	1.50E-01
Vm-13	13	1.07E+00	1.07E+00	PT 7-6	9	-3.78E-01	-3.73E-01
Vm-14	14	1.04E+00	1.04E+00	PT 8-6	10	-2.95E-01	-2.99E-01
Vm-15	15	1.04E+00	1.03E+00	PT 9-6	11	-2.77E-01	-2.76E-01
Vm-16	16	1.04E+00	1.03E+00	PT 10-6	12	-1.58E-01	-1.59E-01
Vm-17	17	1.04E+00	1.04E+00	PT 11-9	13	0.00E+00	0.00E+00
Vm-18	18	1.03E+00	1.03E+00	PT 10-9	14	-2.77E-01	-2.80E-01
Vm-19	19	1.03E+00	1.03E+00	PT 12-4	15	-4.42E-01	-4.50E-01
Vm-20	20	1.03E+00	1.03E+00	PT 13-12	16	0.00E+00	0.00E+00
Vm-21	21	1.03E+00	1.04E+00	PT 14-12	17	-7.78E-02	-7.82E-02
Vm-22	22	1.03E+00	1.04E+00	PT 15-12	18	-1.77E-01	-1.73E-01
Vm-23	23	1.03E+00	1.03E+00	PT 16-12	19	-7.19E-02	-7.12E-02
Vm-24	24	1.02E+00	1.03E+00	PT 15-14	20	-1.58E-02	-1.58E-02
Vm-25	25	1.02E+00	1.01E+00	PT 17-16	21	-3.68E-02	-3.71E-02
Vm-26	26	1.00E+00	1.00E+00	PT 18-15	22	-5.98E-02	-6.00E-02
Vm-27	27	1.02E+00	1.03E+00	PT 19-18	23	-2.77E-02	-2.73E-02
Vm-28	28	1.01E+00	1.01E+00	PT 20-19	24	6.74E-02	6.87E-02
Vm-29	29	1.00E+00	1.00E+00	PT 20-10	25	-8.94E-02	-9.02E-02
Vm-30	30	9.92E-01	9.86E-01	PT 17-10	26	-5.32E-02	-5.37E-02
PG-1	1	2.61E+00	2.61E+00	PT 21-10	27	-1.57E-01	-1.56E-01
PG-2	2	1.83E-01	1.82E-01	PT 22-10	28	-7.57E-02	-7.64E-02
PG-3	3	-2.40E-02	-2.43E-02	PT 22-21	29	1.83E-02	1.84E-02
PG-4	4	-7.60E-02	-7.51E-02	PT 23-15	30	-5.00E-02	-5.07E-02
PG-5	5	-9.42E-01	-9.37E-01	PT 24-22	31	-5.69E-02	-5.68E-02
PG-6	6	0.00E+00	0.00E+00	PT 24-23	32	-1.80E-02	-1.77E-02
PG-7	7	-2.28E-01	-2.31E-01	PT 25-24	33	1.22E-02	1.24E-02
PG-8	8	-3.00E-01	-2.99E-01	PT 26-25	34	-3.50E-02	-3.57E-02
PG-9	9	0.00E+00	0.00E+00	PT 27-25	35	4.79E-02	4.88E-02
PG-10	10	-5.80E-02	-5.71E-02	PT 27-28	36	-1.81E-01	-1.84E-01
PG-11	11	0.00E+00	0.00E+00	PT 29-27	37	-6.10E-02	-6.17E-02
PG-12	12	-1.12E-01	-1.12E-01	PT 30-27	38	-6.93E-02	-6.91E-02
PG-13	13	0.00E+00	0.00E+00	PT 30-29	39	-3.67E-02	-3.67E-02
PG-14	14	-6.20E-02	-6.13E-02	PT 28-8	40	5.47E-03	5.38E-03
PG-15	15	-8.20E-02	-8.13E-02	PT 28-6	41	-1.86E-01	-1.86E-01
PG-16	16	-3.50E-02	-3.49E-02	QF 1-2	1	-2.47E-01	-2.52E-01
PG-17	17	-9.00E-02	-9.13E-02	QF 1-3	2	4.28E-02	4.21E-02
PG-18	18	-3.20E-02	-3.22E-02	QF 2-4	3	4.75E-02	4.81E-02
PG-19	19	-9.50E-02	-9.44E-02	QF 3-4	4	-3.85E-02	-3.94E-02
PG-20	20	-2.20E-02	-2.24E-02	QF 2-5	5	2.78E-02	2.68E-02

PG-21	21	-1.75E-01	-1.78E-01	QF 2-6	6	1.37E-02	1.35E-02
PG-22	22	0.00E+00	0.00E+00	QF 4-6	7	-1.59E-01	-1.58E-01
PG-23	23	-3.20E-02	-3.16E-02	QF 5-7	8	1.15E-01	1.15E-01
PG-24	24	-8.70E-02	-8.56E-02	QF 6-7	9	-2.78E-02	-2.84E-02
PG-25	25	0.00E+00	0.00E+00	QF 6-8	10	-7.20E-02	-7.36E-02
PG-26	26	-3.50E-02	-3.45E-02	QF 6-9	11	-8.09E-02	-8.22E-02
PG-27	27	0.00E+00	0.00E+00	QF 6-10	12	1.87E-03	1.83E-03
PG-28	28	0.00E+00	0.00E+00	QF 9-11	13	-1.56E-01	-1.52E-01
PG-29	29	-2.40E-02	-2.36E-02	QF 9-10	14	5.88E-02	5.80E-02
PG-30	30	-1.06E-01	-1.06E-01	QF 4-12	15	1.44E-01	1.49E-01
QG-1	1	-2.04E-01	-2.06E-01	QF 12-13	16	-1.03E-01	-1.02E-01
QG-2	2	4.34E-01	4.43E-01	QF 12-14	17	2.40E-02	2.37E-02
QG-3	3	-1.20E-02	-1.15E-02	QF 12-15	18	6.79E-02	6.99E-02
QG-4	4	-1.60E-02	-1.54E-02	QF 12-16	19	3.35E-02	3.35E-02
QG-5	5	1.67E-01	1.66E-01	QF 14-15	20	6.46E-03	6.34E-03
QG-6	6	0.00E+00	0.00E+00	QF 16-17	21	1.44E-02	1.39E-02
QG-7	7	-1.09E-01	-1.11E-01	QF 15-18	22	1.60E-02	1.53E-02
QG-8	8	6.11E-02	6.10E-02	QF 18-19	23	6.17E-03	5.93E-03
QG-9	9	0.00E+00	0.00E+00	QF 19-20	24	-2.79E-02	-2.90E-02
QG-10	10	-2.00E-02	-2.07E-02	QF 10-20	25	3.71E-02	3.62E-02
QG-11	11	1.61E-01	1.55E-01	QF 10-17	26	4.43E-02	4.49E-02
QG-12	12	-7.50E-02	-7.27E-02	QF 10-21	27	1.00E-01	9.70E-02
QG-13	13	1.05E-01	1.07E-01	QF 10-22	28	4.60E-02	4.70E-02
QG-14	14	-1.60E-02	-1.63E-02	QF 21-22	29	-1.43E-02	-1.43E-02
QG-15	15	-2.50E-02	-2.55E-02	QF 15-23	30	2.91E-02	2.98E-02
QG-16	16	-1.80E-02	-1.80E-02	QF 22-24	31	3.06E-02	2.95E-02
QG-17	17	-5.80E-02	-5.99E-02	QF 23-24	32	1.24E-02	1.25E-02
QG-18	18	-9.00E-03	-8.73E-03	QF 24-25	33	2.01E-02	1.96E-02
QG-19	19	-3.40E-02	-3.48E-02	QF 25-26	34	2.37E-02	2.33E-02
QG-20	20	-7.00E-03	-7.04E-03	QF 25-27	35	-3.71E-03	-3.82E-03
QG-21	21	-1.12E-01	-1.11E-01	QF 28-27	36	5.04E-02	5.19E-02
QG-22	22	0.00E+00	0.00E+00	QF 27-29	37	1.67E-02	1.61E-02
QG-23	23	-1.60E-02	-1.59E-02	QF 27-30	38	1.66E-02	1.73E-02
QG-24	24	-6.70E-02	-6.66E-02	QF 29-30	39	6.06E-03	6.03E-03
QG-25	25	0.00E+00	0.00E+00	QF 8-28	40	-5.45E-03	-5.62E-03
QG-26	26	-2.30E-02	-2.32E-02	QF 6-27	41	1.15E-03	1.14E-03
QG-27	27	0.00E+00	0.00E+00	QT 2-1	1	3.45E-01	3.36E-01
QG-28	28	0.00E+00	0.00E+00	QT 3-1	2	2.65E-02	2.76E-02
QG-29	29	-9.00E-03	-9.03E-03	QT 4-2	3	-5.54E-02	-5.69E-02
QG-30	30	-1.90E-02	-1.90E-02	QT 4-3	4	5.44E-02	5.25E-02
PF 1-2	1	1.73E+00	1.74E+00	QT 5-2	5	5.17E-02	5.08E-02
PF 1-3	2	8.76E-01	8.71E-01	QT 6-2	6	5.80E-03	6.02E-03
PF 2-4	3	4.37E-01	4.39E-01	QT 6-4	7	1.72E-01	1.77E-01
PF 3-4	4	8.21E-01	8.35E-01	QT 7-5	8	-1.31E-01	-1.29E-01
PF 2-5	5	8.24E-01	8.20E-01	QT 7-6	9	2.23E-02	2.23E-02
PF 2-6	6	6.04E-01	5.99E-01	QT 8-6	10	6.66E-02	6.76E-02
PF 4-6	7	7.21E-01	7.29E-01	QT 9-6	11	9.72E-02	9.72E-02

PF 5-7	8	-1.48E-01	-1.47E-01	QT 10-6	12	1.10E-02	1.06E-02
PF 6-7	9	3.81E-01	3.87E-01	QT 11-9	13	1.61E-01	1.63E-01
PF 6-8	10	2.96E-01	2.92E-01	QT 10-9	14	-5.08E-02	-5.21E-02
PF 6-9	11	2.77E-01	2.72E-01	QT 12-4	15	-9.72E-02	-1.00E-01
PF 6-10	12	1.58E-01	1.60E-01	QT 13-12	16	1.05E-01	1.01E-01
PF 9-11	13	0.00E+00	0.00E+00	QT 14-12	17	-2.25E-02	-2.23E-02
PF 9-10	14	2.77E-01	2.75E-01	QT 15-12	18	-6.36E-02	-6.29E-02
PF 4-12	15	4.42E-01	4.49E-01	QT 16-12	19	-3.24E-02	-3.25E-02
PF 12-13	16	0.00E+00	0.00E+00	QT 15-14	20	-6.40E-03	-6.51E-03
PF 12-14	17	7.86E-02	8.00E-02	QT 17-16	21	-1.41E-02	-1.46E-02
PF 12-15	18	1.79E-01	1.80E-01	QT 18-15	22	-1.52E-02	-1.49E-02
PF 12-16	19	7.24E-02	7.27E-02	QT 19-18	23	-6.07E-03	-6.21E-03
PF 14-15	20	1.58E-02	1.56E-02	QT 20-19	24	2.83E-02	2.82E-02
PF 16-17	21	3.69E-02	3.72E-02	QT 20-10	25	-3.53E-02	-3.63E-02
PF 15-18	22	6.02E-02	5.93E-02	QT 17-10	26	-4.39E-02	-4.37E-02
PF 18-19	23	2.78E-02	2.81E-02	QT 21-10	27	-9.77E-02	-9.57E-02
PF 19-20	24	-6.73E-02	-6.75E-02	QT 22-10	28	-4.49E-02	-4.39E-02
PF 10-20	25	9.03E-02	8.99E-02	QT 22-21	29	1.43E-02	1.45E-02
PF 10-17	26	5.33E-02	5.36E-02	QT 23-15	30	-2.84E-02	-2.85E-02
PF 10-21	27	1.58E-01	1.57E-01	QT 24-22	31	-2.99E-02	-3.08E-02
PF 10-22	28	7.62E-02	7.51E-02	QT 24-23	32	-1.23E-02	-1.24E-02
PF 21-22	29	-1.83E-02	-1.79E-02	QT 25-24	33	-2.00E-02	-1.97E-02
PF 15-23	30	5.04E-02	5.11E-02	QT 26-25	34	-2.30E-02	-2.24E-02
PF 22-24	31	5.74E-02	5.80E-02	QT 27-25	35	4.17E-03	4.24E-03
PF 23-24	32	1.80E-02	1.79E-02	QT 27-28	36	-3.75E-02	-3.79E-02
PF 24-25	33	-1.21E-02	-1.18E-02	QT 29-27	37	-1.51E-02	-1.52E-02
PF 25-26	34	3.54E-02	3.57E-02	QT 30-27	38	-1.36E-02	-1.32E-02
PF 25-27	35	-4.76E-02	-4.80E-02	QT 30-29	39	-5.42E-03	-5.45E-03
PF 28-27	36	1.81E-01	1.79E-01	QT 28-8	40	-3.80E-02	-3.95E-02
PF 27-29	37	6.19E-02	6.31E-02	QT 28-6	41	-1.23E-02	-1.19E-02

A.2.5. Measurement Distribution for Test Case

Table A.8 IEEE 30 Bus System – Measurement Distribution for Test Case

Type	Index	Actual	Measurement	Type	Index	Actual	Measurement
Vm-1	1	1.060E+00	1.055E+00	PF 23-24	32	1.804E-02	1.794E-02
Vm-3	3	1.021E+00	1.024E+00	PF 24-25	33	-1.208E-02	-1.184E-02
Vm-4	4	1.012E+00	1.013E+00	PF 25-26	34	3.545E-02	3.568E-02
Vm-5	5	1.010E+00	1.018E+00	PF 25-27	35	-4.763E-02	-4.804E-02
Vm-8	8	1.010E+00	1.001E+00	PF 28-27	36	1.807E-01	1.793E-01
Vm-10	10	1.045E+00	1.049E+00	PF 27-30	38	7.092E-02	7.224E-02
Vm-12	12	1.057E+00	1.056E+00	PF 29-30	39	3.704E-02	3.706E-02
Vm-18	18	1.028E+00	1.029E+00	PT 2-1	1	-1.681E+00	-1.654E+00
Vm-21	21	1.033E+00	1.043E+00	PT 4-3	4	-8.129E-01	-8.014E-01
Vm-24	24	1.022E+00	1.025E+00	PT 6-2	6	-5.843E-01	-5.796E-01

Vm-25	25	1.018E+00	1.010E+00	PT 10-9	14	-2.772E-01	-2.796E-01
Vm-26	26	9.999E-01	1.002E+00	PT 12-4	15	-4.419E-01	-4.497E-01
Vm-28	28	1.007E+00	1.005E+00	PT 15-12	18	-1.767E-01	-1.733E-01
Vm-29	29	1.004E+00	1.004E+00	PT 20-19	24	6.744E-02	6.871E-02
PG-1	1	2.610E+00	2.610E+00	PT 20-10	25	-8.944E-02	-9.019E-02
PG-2	2	1.830E-01	1.822E-01	PT 21-10	27	-1.567E-01	-1.564E-01
PG-4	4	-7.600E-02	-7.509E-02	PT 22-21	29	1.826E-02	1.840E-02
PG-5	5	-9.420E-01	-9.366E-01	PT 23-15	30	-5.004E-02	-5.072E-02
PG-7	7	-2.280E-01	-2.306E-01	PT 24-22	31	-5.694E-02	-5.681E-02
PG-9	9	0.000E+00	0.000E+00	PT 24-23	32	-1.798E-02	-1.766E-02
PG-10	10	-5.800E-02	-5.712E-02	PT 27-28	36	-1.807E-01	-1.842E-01
PG-14	14	-6.200E-02	-6.134E-02	PT 30-29	39	-3.670E-02	-3.673E-02
PG-15	15	-8.200E-02	-8.133E-02	PT 28-8	40	5.468E-03	5.381E-03
PG-16	16	-3.500E-02	-3.488E-02	QF 1-3	2	4.285E-02	4.207E-02
PG-18	18	-3.200E-02	-3.216E-02	QF 2-4	3	4.750E-02	4.811E-02
PG-19	19	-9.500E-02	-9.437E-02	QF 2-5	5	2.782E-02	2.676E-02
PG-21	21	-1.750E-01	-1.780E-01	QF 4-6	7	-1.591E-01	-1.583E-01
PG-24	24	-8.700E-02	-8.560E-02	QF 5-7	8	1.149E-01	1.149E-01
PG-29	29	-2.400E-02	-2.361E-02	QF 6-7	9	-2.781E-02	-2.836E-02
PG-30	30	-1.060E-01	-1.057E-01	QF 6-8	10	-7.196E-02	-7.362E-02
QG-1	1	-2.042E-01	-2.064E-01	QF 6-9	11	-8.093E-02	-8.216E-02
QG-2	2	4.337E-01	4.435E-01	QF 9-11	13	-1.560E-01	-1.516E-01
QG-4	4	-1.600E-02	-1.542E-02	QF 12-13	16	-1.032E-01	-1.023E-01
QG-5	5	1.666E-01	1.659E-01	QF 12-14	17	2.400E-02	2.372E-02
QG-7	7	-1.090E-01	-1.109E-01	QF 12-16	19	3.349E-02	3.352E-02
QG-9	9	0.000E+00	0.000E+00	QF 14-15	20	6.458E-03	6.339E-03
QG-10	10	-2.000E-02	-2.070E-02	QF 15-18	22	1.595E-02	1.534E-02
QG-14	14	-1.600E-02	-1.629E-02	QF 18-19	23	6.167E-03	5.930E-03
QG-15	15	-2.500E-02	-2.552E-02	QF 10-17	26	4.429E-02	4.488E-02
QG-16	16	-1.800E-02	-1.805E-02	QF 22-24	31	3.062E-02	2.953E-02
QG-18	18	-9.000E-03	-8.734E-03	QF 23-24	32	1.244E-02	1.248E-02
QG-19	19	-3.400E-02	-3.480E-02	QF 24-25	33	2.013E-02	1.958E-02
QG-21	21	-1.120E-01	-1.106E-01	QF 25-26	34	2.367E-02	2.335E-02
QG-24	24	-6.700E-02	-6.658E-02	QF 25-27	35	-3.712E-03	-3.823E-03
QG-30	30	-1.900E-02	-1.901E-02	QF 28-27	36	5.036E-02	5.187E-02
PF 1-3	2	8.765E-01	8.707E-01	QF 27-30	38	1.663E-02	1.728E-02
PF 2-4	3	4.365E-01	4.395E-01	QF 29-30	39	6.059E-03	6.025E-03
PF 2-5	5	8.236E-01	8.199E-01	QT 2-1	1	3.447E-01	3.363E-01
PF 4-6	7	7.213E-01	7.291E-01	QT 4-3	4	5.443E-02	5.248E-02
PF 5-7	8	-1.478E-01	-1.474E-01	QT 6-2	6	5.802E-03	6.021E-03
PF 6-7	9	3.813E-01	3.870E-01	QT 10-9	14	-5.082E-02	-5.207E-02
PF 6-8	10	2.956E-01	2.917E-01	QT 12-4	15	-9.721E-02	-1.004E-01
PF 6-9	11	2.772E-01	2.717E-01	QT 15-12	18	-6.363E-02	-6.288E-02
PF 6-10	12	1.584E-01	1.596E-01	QT 20-19	24	2.827E-02	2.821E-02
PF 9-11	13	0.000E+00	0.000E+00	QT 20-10	25	-3.527E-02	-3.632E-02
PF 12-13	16	0.000E+00	0.000E+00	QT 21-10	27	-9.771E-02	-9.566E-02
PF 12-14	17	7.858E-02	7.998E-02	QT 22-21	29	1.430E-02	1.449E-02

PF 12-16	19	7.244E-02	7.267E-02	QT 23-15	30	-2.844E-02	-2.848E-02
PF 14-15	20	1.583E-02	1.564E-02	QT 24-22	31	-2.991E-02	-3.078E-02
PF 15-18	22	6.017E-02	5.930E-02	QT 24-23	32	-1.232E-02	-1.240E-02
PF 18-19	23	2.778E-02	2.808E-02	QT 27-28	36	-3.749E-02	-3.788E-02
PF 10-17	26	5.332E-02	5.355E-02	QT 30-29	39	-5.425E-03	-5.448E-03
PF 22-24	31	5.739E-02	5.796E-02	QT 28-8	40	-3.803E-02	-3.946E-02

A.3. IEEE 118 Bus System Data

A.3.1. Single Line Diagram

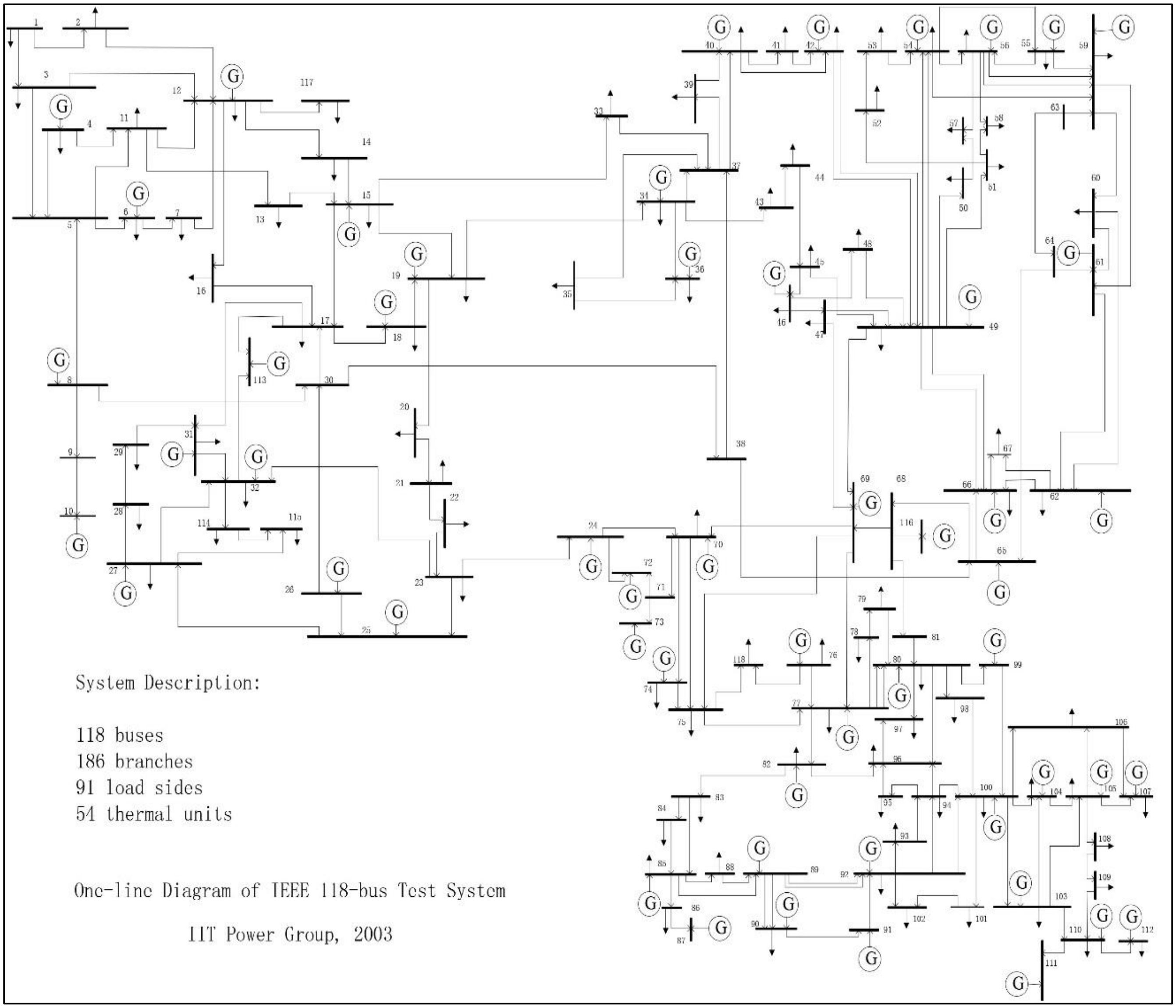

Figure A.3 IEEE 118 Bus System – Single Line Diagram [47]

A.3.2. Line Data

Table A.9 IEEE 118 Bus System – Line Data

From Bus	To Bus	R	X	B	Tap Setting

1	2	0.0303	0.0999	0.0254	0
1	3	0.0129	0.0424	0.01082	0
4	5	0.00176	0.00798	0.0021	0
3	5	0.0241	0.108	0.0284	0
5	6	0.0119	0.054	0.01426	0
6	7	0.00459	0.0208	0.0055	0
8	9	0.00244	0.0305	1.162	0
8	5	0	0.0267	0	0.985
9	10	0.00258	0.0322	1.23	0
4	11	0.0209	0.0688	0.01748	0
5	11	0.0203	0.0682	0.01738	0
11	12	0.00595	0.0196	0.00502	0
2	12	0.0187	0.0616	0.01572	0
3	12	0.0484	0.16	0.0406	0
7	12	0.00862	0.034	0.00874	0
11	13	0.02225	0.0731	0.01876	0
12	14	0.0215	0.0707	0.01816	0
13	15	0.0744	0.2444	0.06268	0
14	15	0.0595	0.195	0.0502	0
12	16	0.0212	0.0834	0.0214	0
15	17	0.0132	0.0437	0.0444	0
16	17	0.0454	0.1801	0.0466	0
17	18	0.0123	0.0505	0.01298	0
18	19	0.01119	0.0493	0.01142	0
19	20	0.0252	0.117	0.0298	0
15	19	0.012	0.0394	0.0101	0
20	21	0.0183	0.0849	0.0216	0
21	22	0.0209	0.097	0.0246	0
22	23	0.0342	0.159	0.0404	0
23	24	0.0135	0.0492	0.0498	0
23	25	0.0156	0.08	0.0864	0
26	25	0	0.0382	0	0.96
25	27	0.0318	0.163	0.1764	0
27	28	0.01913	0.0855	0.0216	0
28	29	0.0237	0.0943	0.0238	0
30	17	0	0.0388	0	0.96
8	30	0.00431	0.0504	0.514	0
26	30	0.00799	0.086	0.908	0
17	31	0.0474	0.1563	0.0399	0
29	31	0.0108	0.0331	0.0083	0
23	32	0.0317	0.1153	0.1173	0
31	32	0.0298	0.0985	0.0251	0
27	32	0.0229	0.0755	0.01926	0
15	33	0.038	0.1244	0.03194	0
19	34	0.0752	0.247	0.0632	0
35	36	0.00224	0.0102	0.00268	0
35	37	0.011	0.0497	0.01318	0

33	37	0.0415	0.142	0.0366	0
34	36	0.00871	0.0268	0.00568	0
34	37	0.00256	0.0094	0.00984	0
38	37	0	0.0375	0	0.935
37	39	0.0321	0.106	0.027	0
37	40	0.0593	0.168	0.042	0
30	38	0.00464	0.054	0.422	0
39	40	0.0184	0.0605	0.01552	0
40	41	0.0145	0.0487	0.01222	0
40	42	0.0555	0.183	0.0466	0
41	42	0.041	0.135	0.0344	0
43	44	0.0608	0.2454	0.06068	0
34	43	0.0413	0.1681	0.04226	0
44	45	0.0224	0.0901	0.0224	0
45	46	0.04	0.1356	0.0332	0
46	47	0.038	0.127	0.0316	0
46	48	0.0601	0.189	0.0472	0
47	49	0.0191	0.0625	0.01604	0
42	49	0.0715	0.323	0.086	0
42	49	0.0715	0.323	0.086	0
45	49	0.0684	0.186	0.0444	0
48	49	0.0179	0.0505	0.01258	0
49	50	0.0267	0.0752	0.01874	0
49	51	0.0486	0.137	0.0342	0
51	52	0.0203	0.0588	0.01396	0
52	53	0.0405	0.1635	0.04058	0
53	54	0.0263	0.122	0.031	0
49	54	0.073	0.289	0.0738	0
49	54	0.0869	0.291	0.073	0
54	55	0.0169	0.0707	0.0202	0
54	56	0.00275	0.00955	0.00732	0
55	56	0.00488	0.0151	0.00374	0
56	57	0.0343	0.0966	0.0242	0
50	57	0.0474	0.134	0.0332	0
56	58	0.0343	0.0966	0.0242	0
51	58	0.0255	0.0719	0.01788	0
54	59	0.0503	0.2293	0.0598	0
56	59	0.0825	0.251	0.0569	0
56	59	0.0803	0.239	0.0536	0
55	59	0.04739	0.2158	0.05646	0
59	60	0.0317	0.145	0.0376	0
59	61	0.0328	0.15	0.0388	0
60	61	0.00264	0.0135	0.01456	0
60	62	0.0123	0.0561	0.01468	0
61	62	0.00824	0.0376	0.0098	0
63	59	0	0.0386	0	0.96
63	64	0.00172	0.02	0.216	0

64	61	0	0.0268	0	0.985
38	65	0.00901	0.0986	1.046	0
64	65	0.00269	0.0302	0.38	0
49	66	0.018	0.0919	0.0248	0
49	66	0.018	0.0919	0.0248	0
62	66	0.0482	0.218	0.0578	0
62	67	0.0258	0.117	0.031	0
65	66	0	0.037	0	0.935
66	67	0.0224	0.1015	0.02682	0
65	68	0.00138	0.016	0.638	0
47	69	0.0844	0.2778	0.07092	0
49	69	0.0985	0.324	0.0828	0
68	69	0	0.037	0	0.935
69	70	0.03	0.127	0.122	0
24	70	0.00221	0.4115	0.10198	0
70	71	0.00882	0.0355	0.00878	0
24	72	0.0488	0.196	0.0488	0
71	72	0.0446	0.18	0.04444	0
71	73	0.00866	0.0454	0.01178	0
70	74	0.0401	0.1323	0.03368	0
70	75	0.0428	0.141	0.036	0
69	75	0.0405	0.122	0.124	0
74	75	0.0123	0.0406	0.01034	0
76	77	0.0444	0.148	0.0368	0
69	77	0.0309	0.101	0.1038	0
75	77	0.0601	0.1999	0.04978	0
77	78	0.00376	0.0124	0.01264	0
78	79	0.00546	0.0244	0.00648	0
77	80	0.017	0.0485	0.0472	0
77	80	0.0294	0.105	0.0228	0
79	80	0.0156	0.0704	0.0187	0
68	81	0.00175	0.0202	0.808	0
81	80	0	0.037	0	0.935
77	82	0.0298	0.0853	0.08174	0
82	83	0.0112	0.03665	0.03796	0
83	84	0.0625	0.132	0.0258	0
83	85	0.043	0.148	0.0348	0
84	85	0.0302	0.0641	0.01234	0
85	86	0.035	0.123	0.0276	0
86	87	0.02828	0.2074	0.0445	0
85	88	0.02	0.102	0.0276	0
85	89	0.0239	0.173	0.047	0
88	89	0.0139	0.0712	0.01934	0
89	90	0.0518	0.188	0.0528	0
89	90	0.0238	0.0997	0.106	0
90	91	0.0254	0.0836	0.0214	0
89	92	0.0099	0.0505	0.0548	0

89	92	0.0393	0.1581	0.0414	0
91	92	0.0387	0.1272	0.03268	0
92	93	0.0258	0.0848	0.0218	0
92	94	0.0481	0.158	0.0406	0
93	94	0.0223	0.0732	0.01876	0
94	95	0.0132	0.0434	0.0111	0
80	96	0.0356	0.182	0.0494	0
82	96	0.0162	0.053	0.0544	0
94	96	0.0269	0.0869	0.023	0
80	97	0.0183	0.0934	0.0254	0
80	98	0.0238	0.108	0.0286	0
80	99	0.0454	0.206	0.0546	0
92	100	0.0648	0.295	0.0472	0
94	100	0.0178	0.058	0.0604	0
95	96	0.0171	0.0547	0.01474	0
96	97	0.0173	0.0885	0.024	0
98	100	0.0397	0.179	0.0476	0
99	100	0.018	0.0813	0.0216	0
100	101	0.0277	0.1262	0.0328	0
92	102	0.0123	0.0559	0.01464	0
101	102	0.0246	0.112	0.0294	0
100	103	0.016	0.0525	0.0536	0
100	104	0.0451	0.204	0.0541	0
103	104	0.0466	0.1584	0.0407	0
103	105	0.0535	0.1625	0.0408	0
100	106	0.0605	0.229	0.062	0
104	105	0.00994	0.0378	0.00986	0
105	106	0.014	0.0547	0.01434	0
105	107	0.053	0.183	0.0472	0
105	108	0.0261	0.0703	0.01844	0
106	107	0.053	0.183	0.0472	0
108	109	0.0105	0.0288	0.0076	0
103	110	0.03906	0.1813	0.0461	0
109	110	0.0278	0.0762	0.0202	0
110	111	0.022	0.0755	0.02	0
110	112	0.0247	0.064	0.062	0
17	113	0.00913	0.0301	0.00768	0
32	113	0.0615	0.203	0.0518	0
32	114	0.0135	0.0612	0.01628	0
27	115	0.0164	0.0741	0.01972	0
114	115	0.0023	0.0104	0.00276	0
68	116	0.00034	0.00405	0.164	0
12	117	0.0329	0.14	0.0358	0
75	118	0.0145	0.0481	0.01198	0
76	118	0.0164	0.0544	0.01356	0

A.3.3. Bus Data

Table A.10 IEEE 118 Bus System – Bus Data

Sr	Bus Type	|V|	Generation		Load		Generation Limits	
			MW	MVAR	MW	MVAR	Max	Min
1	2	0.955	0	0	51	27	15	-5
2	1	0.971	0	0	20	9	-	-
3	1	0.968	0	0	39	10	-	-
4	2	0.998	0	0	39	12	300	-300
5	1	1.002	0	0	0	0	-	-
6	2	0.99	0	0	52	22	50	-13
7	1	0.989	0	0	19	2	-	-
8	2	1.015	0	0	28	0	300	-300
9	1	1.043	0	0	0	0	-	-
10	2	1.05	450	0	0	0	200	-147
11	1	0.985	0	0	70	23	-	-
12	2	0.99	85	0	47	10	120	-35
13	1	0.968	0	0	34	16	-	-
14	1	0.984	0	0	14	1	-	-
15	2	0.97	0	0	90	30	30	-10
16	1	0.984	0	0	25	10	-	-
17	1	0.995	0	0	11	3	-	-
18	2	0.973	0	0	60	34	50	-16
19	2	0.963	0	0	45	25	24	-8
20	1	0.958	0	0	18	3	-	-
21	1	0.959	0	0	14	8	-	-
22	1	0.97	0	0	10	5	-	-
23	1	1	0	0	7	3	-	-
24	2	0.992	0	0	13	0	300	-300
25	2	1.05	220	0	0	0	140	-47
26	2	1.015	314	0	0	0	1000	-1000
27	2	0.968	0	0	71	13	300	-300
28	1	0.962	0	0	17	7	-	-
29	1	0.963	0	0	24	4	-	-
30	1	0.968	0	0	0	0	-	-
31	2	0.967	7	0	43	27	300	-300
32	2	0.964	0	0	59	23	42	-14
33	1	0.972	0	0	23	9	-	-
34	2	0.986	0	0	59	26	24	-8
35	1	0.981	0	0	33	9	-	-
36	2	0.98	0	0	31	17	24	-8
37	1	0.992	0	0	0	0	-	-
38	1	0.962	0	0	0	0	-	-
39	1	0.97	0	0	27	11	-	-

40	2	0.97	0	0	66	23	300	-300
41	1	0.967	0	0	37	10	-	-
42	2	0.985	0	0	96	23	300	-300
43	1	0.978	0	0	18	7	-	-
44	1	0.985	0	0	16	8	-	-
45	1	0.987	0	0	53	22	-	-
46	2	1.005	19	0	28	10	100	-100
47	1	1.017	0	0	34	0	-	-
48	1	1.021	0	0	20	11	-	-
49	2	1.025	204	0	87	30	210	-85
50	1	1.001	0	0	17	4	-	-
51	1	0.967	0	0	17	8	-	-
52	1	0.957	0	0	18	5	-	-
53	1	0.946	0	0	23	11	-	-
54	2	0.955	48	0	113	32	300	-300
55	2	0.952	0	0	63	22	23	-8
56	2	0.954	0	0	84	18	15	-8
57	1	0.971	0	0	12	3	-	-
58	1	0.959	0	0	12	3	-	-
59	2	0.985	155	0	277	113	180	-60
60	1	0.993	0	0	78	3	-	-
61	2	0.995	160	0	0	0	300	-100
62	2	0.998	0	0	77	14	20	-20
63	1	0.969	0	0	0	0	-	-
64	1	0.984	0	0	0	0	-	-
65	2	1.005	391	0	0	0	200	-67
66	2	1.05	392	0	39	18	200	-67
67	1	1.02	0	0	28	7	-	-
68	1	1.003	0	0	0	0	-	-
69	3	1.035	516.4	0	0	0	300	-300
70	2	0.984	0	0	66	20	32	-10
71	1	0.987	0	0	0	0	-	-
72	2	0.98	0	0	12	0	100	-100
73	2	0.991	0	0	6	0	100	-100
74	2	0.958	0	0	68	27	9	-6
75	1	0.967	0	0	47	11	-	-
76	2	0.943	0	0	68	36	-	-
77	2	1.006	0	0	61	28	23	-8
78	1	1.003	0	0	71	26	70	-20
79	1	1.009	0	0	39	32	-	-
80	2	1.04	477	0	130	26	280	-165
81	1	0.997	0	0	0	0	-	-
82	1	0.989	0	0	54	27	-	-
83	1	0.985	0	0	20	10	-	-
84	1	0.98	0	0	11	7	-	-
85	2	0.985	0	0	24	15	23	-8

86	1	0.987	0	0	21	10	-	-
87	2	1.015	4	0	0	0	1000	-100
88	1	0.987	0	0	48	10	-	-
89	2	1.005	607	0	0	0	300	-210
90	2	0.985	0	0	163	42	300	-300
91	2	0.98	0	0	10	0	100	-100
92	2	0.993	0	0	65	10	9	-3
93	1	0.987	0	0	12	7	-	-
94	1	0.991	0	0	30	16	-	-
95	1	0.981	0	0	42	31	-	-
96	1	0.993	0	0	38	15	-	-
97	1	1.011	0	0	15	9	-	-
98	1	1.024	0	0	34	8	-	-
99	2	1.01	0	0	42	0	100	-100
100	2	1.017	252	0	37	18	155	-50
101	1	0.993	0	0	22	15	-	-
102	1	0.991	0	0	5	3	-	-
103	2	1.001	40	0	23	16	40	-15
104	2	0.971	0	0	38	25	23	-8
105	2	0.965	0	0	31	26	23	-8
106	1	0.962	0	0	43	16	-	-
107	2	0.952	0	0	50	12	200	-200
108	1	0.967	0	0	2	1	-	-
109	1	0.967	0	0	8	3	-	-
110	2	0.973	0	0	39	30	23	-8
111	2	0.98	36	0	0	0	1000	-100
112	2	0.975	0	0	68	13	1000	-100
113	2	0.993	0	0	6	0	200	-100
114	1	0.96	0	0	8	3	-	-
115	1	0.96	0	0	22	7	-	-
116	2	1.005	0	0	184	0	1000	-1000
117	1	0.974	0	0	20	8	-	-
118	1	0.949	0	0	33	15	-	-

A.3.4. Load Flow Data and Simulated Measurements

Table A.11 IEEE 118 Bus System - Load Flow Data and Simulated Measurements

Type	Index	Actual	Measurement	Type	Index	Actual	Measurement
Vm-1	1	9.55E-01	9.60E-01	PT 4-11	10	-6.34E-01	-6.26E-01
Vm-2	2	9.71E-01	9.69E-01	PT 5-11	11	-7.60E-01	-7.52E-01
Vm-3	3	9.68E-01	9.69E-01	PT 11-12	12	-3.41E-01	-3.44E-01
Vm-4	4	9.98E-01	9.89E-01	PT 2-12	13	3.27E-01	3.22E-01
Vm-5	5	1.00E+00	9.94E-01	PT 3-12	14	9.89E-02	9.71E-02
Vm-6	6	9.90E-01	9.91E-01	PT 7-12	15	-1.65E-01	-1.67E-01

Vm-7	7	9.89E-01	9.83E-01	PT 11-13	16	-3.48E-01	-3.45E-01
Vm-8	8	1.02E+00	1.02E+00	PT 12-14	17	-1.82E-01	-1.80E-01
Vm-9	9	1.04E+00	1.05E+00	PT 13-15	18	-7.67E-03	-7.75E-03
Vm-10	10	1.05E+00	1.05E+00	PT 14-15	19	-4.21E-02	-4.15E-02
Vm-11	11	9.85E-01	9.83E-01	PT 12-16	20	-7.49E-02	-7.35E-02
Vm-12	12	9.90E-01	9.83E-01	PT 15-17	21	1.05E+00	1.07E+00
Vm-13	13	9.68E-01	9.66E-01	PT 16-17	22	1.77E-01	1.73E-01
Vm-14	14	9.84E-01	9.89E-01	PT 17-18	23	-7.94E-01	-7.95E-01
Vm-15	15	9.70E-01	9.70E-01	PT 18-19	24	-1.93E-01	-1.96E-01
Vm-16	16	9.84E-01	9.76E-01	PT 19-20	25	1.07E-01	1.08E-01
Vm-17	17	9.95E-01	1.00E+00	PT 15-19	26	-1.15E-01	-1.13E-01
Vm-18	18	9.73E-01	9.77E-01	PT 20-21	27	2.88E-01	2.92E-01
Vm-19	19	9.62E-01	9.71E-01	PT 21-22	28	4.33E-01	4.25E-01
Vm-20	20	9.57E-01	9.60E-01	PT 22-23	29	5.43E-01	5.34E-01
Vm-21	21	9.58E-01	9.60E-01	PT 23-24	30	-8.25E-02	-8.32E-02
Vm-22	22	9.69E-01	9.68E-01	PT 23-25	31	1.67E+00	1.70E+00
Vm-23	23	9.99E-01	1.00E+00	PT 26-25	32	-9.03E-01	-9.03E-01
Vm-24	24	9.92E-01	9.87E-01	PT 25-27	33	-1.37E+0	-1.39E+00
Vm-25	25	1.05E+00	1.05E+00	PT 27-28	34	-3.27E-01	-3.30E-01
Vm-26	26	1.02E+00	1.02E+00	PT 28-29	35	-1.56E-01	-1.56E-01
Vm-27	27	9.68E-01	9.73E-01	PT 30-17	36	-2.31E+0	-2.34E+00
Vm-28	28	9.62E-01	9.60E-01	PT 8-30	37	-7.38E-01	-7.44E-01
Vm-29	29	9.63E-01	9.70E-01	PT 26-30	38	-2.20E+0	-2.19E+00
Vm-30	30	9.85E-01	9.89E-01	PT 17-31	39	-1.46E-01	-1.47E-01
Vm-31	31	9.67E-01	9.65E-01	PT 29-31	40	8.43E-02	8.48E-02
Vm-32	32	9.63E-01	9.71E-01	PT 23-32	41	-9.02E-01	-9.15E-01
Vm-33	33	9.71E-01	9.61E-01	PT 31-32	42	3.02E-01	3.01E-01
Vm-34	34	9.84E-01	9.92E-01	PT 27-32	43	-1.25E-01	-1.23E-01
Vm-35	35	9.80E-01	9.82E-01	PT 15-33	44	-7.28E-02	-7.18E-02
Vm-36	36	9.80E-01	9.87E-01	PT 19-34	45	3.65E-02	3.60E-02
Vm-37	37	9.91E-01	9.97E-01	PT 35-36	46	-8.38E-03	-8.35E-03
Vm-38	38	9.61E-01	9.57E-01	PT 35-37	47	3.40E-01	3.41E-01
Vm-39	39	9.70E-01	9.74E-01	PT 33-37	48	1.59E-01	1.58E-01
Vm-40	40	9.70E-01	9.75E-01	PT 34-36	49	-3.02E-01	-3.06E-01
Vm-41	41	9.67E-01	9.64E-01	PT 34-37	50	9.46E-01	9.49E-01
Vm-42	42	9.85E-01	9.80E-01	PT 38-37	51	-2.43E+0	-2.45E+00
Vm-43	43	9.77E-01	9.78E-01	PT 37-39	52	-5.39E-01	-5.48E-01
Vm-44	44	9.84E-01	9.75E-01	PT 37-40	53	-4.28E-01	-4.27E-01
Vm-45	45	9.86E-01	9.90E-01	PT 30-38	54	-6.21E-01	-6.12E-01
Vm-46	46	1.01E+00	1.01E+00	PT 39-40	55	-2.68E-01	-2.65E-01
Vm-47	47	1.02E+00	1.02E+00	PT 40-41	56	-1.54E-01	-1.54E-01
Vm-48	48	1.02E+00	1.02E+00	PT 40-42	57	1.19E-01	1.20E-01
Vm-49	49	1.03E+00	1.03E+00	PT 41-42	58	2.18E-01	2.18E-01
Vm-50	50	1.00E+00	1.01E+00	PT 43-44	59	1.68E-01	1.69E-01
Vm-51	51	9.67E-01	9.76E-01	PT 34-43	60	-1.41E-02	-1.42E-02
Vm-52	52	9.57E-01	9.60E-01	PT 44-45	61	3.30E-01	3.36E-01
Vm-53	53	9.46E-01	9.41E-01	PT 45-46	62	3.69E-01	3.69E-01

Vm-54	54	9.55E-01	9.51E-01	PT 46-47	63	3.15E-01	3.20E-01
Vm-55	55	9.52E-01	9.52E-01	PT 46-48	64	1.49E-01	1.47E-01
Vm-56	56	9.54E-01	9.51E-01	PT 47-49	65	9.57E-02	9.60E-02
Vm-57	57	9.71E-01	9.65E-01	PT 42-49	66	6.80E-01	6.89E-01
Vm-58	58	9.59E-01	9.50E-01	PT 42-49	67	6.80E-01	6.75E-01
Vm-59	59	9.85E-01	9.91E-01	PT 45-49	68	5.14E-01	5.13E-01
Vm-60	60	9.93E-01	9.92E-01	PT 48-49	69	3.51E-01	3.51E-01
Vm-61	61	9.95E-01	9.88E-01	PT 49-50	70	-5.29E-01	-5.21E-01
Vm-62	62	9.98E-01	9.92E-01	PT 49-51	71	-6.43E-01	-6.55E-01
Vm-63	63	9.69E-01	9.65E-01	PT 51-52	72	-2.84E-01	-2.87E-01
Vm-64	64	9.84E-01	9.78E-01	PT 52-53	73	-1.03E-01	-1.03E-01
Vm-65	65	1.01E+00	1.01E+00	PT 53-54	74	1.27E-01	1.25E-01
Vm-66	66	1.05E+00	1.06E+00	PT 49-54	75	-3.66E-01	-3.60E-01
Vm-67	67	1.02E+00	1.01E+00	PT 49-54	76	-3.64E-01	-3.70E-01
Vm-68	68	1.00E+00	9.98E-01	PT 54-55	77	-7.06E-02	-7.02E-02
Vm-69	69	1.04E+00	1.04E+00	PT 54-56	78	-1.85E-01	-1.86E-01
Vm-70	70	9.84E-01	9.89E-01	PT 55-56	79	2.14E-01	2.18E-01
Vm-71	71	9.87E-01	9.89E-01	PT 56-57	80	2.32E-01	2.34E-01
Vm-72	72	9.80E-01	9.70E-01	PT 50-57	81	-3.52E-01	-3.46E-01
Vm-73	73	9.91E-01	9.97E-01	PT 56-58	82	6.69E-02	6.61E-02
Vm-74	74	9.58E-01	9.62E-01	PT 51-58	83	-1.87E-01	-1.88E-01
Vm-75	75	9.67E-01	9.58E-01	PT 54-59	84	3.09E-01	3.03E-01
Vm-76	76	9.43E-01	9.42E-01	PT 56-59	85	2.87E-01	2.83E-01
Vm-77	77	1.01E+00	1.01E+00	PT 56-59	86	3.01E-01	3.04E-01
Vm-78	78	1.00E+00	9.94E-01	PT 55-59	87	3.52E-01	3.46E-01
Vm-79	79	1.01E+00	1.01E+00	PT 59-60	88	4.39E-01	4.43E-01
Vm-80	80	1.04E+00	1.05E+00	PT 59-61	89	5.26E-01	5.18E-01
Vm-81	81	9.97E-01	1.01E+00	PT 60-61	90	1.12E+00	1.10E+00
Vm-82	82	9.89E-01	9.90E-01	PT 60-62	91	9.89E-02	9.74E-02
Vm-83	83	9.84E-01	9.76E-01	PT 61-62	92	-2.54E-01	-2.58E-01
Vm-84	84	9.80E-01	9.77E-01	PT 63-59	93	-1.52E+0	-1.50E+00
Vm-85	85	9.85E-01	9.76E-01	PT 63-64	94	1.52E+00	1.54E+00
Vm-86	86	9.87E-01	9.87E-01	PT 64-61	95	-3.05E-01	-3.07E-01
Vm-87	87	1.02E+00	1.01E+00	PT 38-65	96	1.84E+00	1.87E+00
Vm-88	88	9.87E-01	9.78E-01	PT 64-65	97	1.84E+00	1.83E+00
Vm-89	89	1.01E+00	1.01E+00	PT 49-66	98	1.35E+00	1.35E+00
Vm-90	90	9.85E-01	9.89E-01	PT 49-66	99	1.35E+00	1.36E+00
Vm-91	91	9.80E-01	9.87E-01	PT 62-66	100	3.79E-01	3.83E-01
Vm-92	92	9.90E-01	9.81E-01	PT 62-67	101	2.45E-01	2.41E-01
Vm-93	93	9.85E-01	9.93E-01	PT 65-66	102	-8.54E-02	-8.71E-02
Vm-94	94	9.90E-01	9.92E-01	PT 66-67	103	-5.25E-01	-5.21E-01
Vm-95	95	9.80E-01	9.81E-01	PT 65-68	104	-1.42E-01	-1.39E-01
Vm-96	96	9.92E-01	1.00E+00	PT 47-69	105	5.87E-01	5.91E-01
Vm-97	97	1.01E+00	1.01E+00	PT 49-69	106	4.88E-01	4.91E-01
Vm-98	98	1.02E+00	1.02E+00	PT 68-69	107	1.26E+00	1.24E+00
Vm-99	99	1.01E+00	1.01E+00	PT 69-70	108	-1.05E+0	-1.03E+00
Vm-100	100	1.02E+00	1.02E+00	PT 24-70	109	6.22E-02	6.17E-02

Vm-101	101	9.91E-01	9.86E-01	PT 70-71	110	-1.66E-01	-1.64E-01
Vm-102	102	9.89E-01	9.92E-01	PT 24-72	111	-1.45E-02	-1.48E-02
Vm-103	103	1.01E+00	1.01E+00	PT 71-72	112	-1.06E-01	-1.04E-01
Vm-104	104	9.71E-01	9.76E-01	PT 71-73	113	-6.00E-02	-6.08E-02
Vm-105	105	9.65E-01	9.74E-01	PT 70-74	114	-1.60E-01	-1.60E-01
Vm-106	106	9.61E-01	9.58E-01	PT 70-75	115	1.94E-03	1.90E-03
Vm-107	107	9.52E-01	9.53E-01	PT 69-75	116	-1.05E+0	-1.07E+00
Vm-108	108	9.66E-01	9.61E-01	PT 74-75	117	5.24E-01	5.25E-01
Vm-109	109	9.67E-01	9.72E-01	PT 76-77	118	6.32E-01	6.21E-01
Vm-110	110	9.73E-01	9.83E-01	PT 69-77	119	-6.10E-01	-6.04E-01
Vm-111	111	9.80E-01	9.78E-01	PT 75-77	120	3.54E-01	3.48E-01
Vm-112	112	9.75E-01	9.67E-01	PT 77-78	121	-4.53E-01	-4.53E-01
Vm-113	113	9.93E-01	9.86E-01	PT 78-79	122	2.57E-01	2.58E-01
Vm-114	114	9.60E-01	9.65E-01	PT 77-80	123	9.83E-01	9.66E-01
Vm-115	115	9.60E-01	9.64E-01	PT 77-80	124	4.50E-01	4.48E-01
Vm-116	116	1.01E+00	9.99E-01	PT 79-80	125	6.55E-01	6.67E-01
Vm-117	117	9.74E-01	9.70E-01	PT 68-81	126	4.42E-01	4.34E-01
Vm-118	118	9.49E-01	9.52E-01	PT 81-80	127	4.42E-01	4.49E-01
PG-1	1	-5.10E-01	-5.08E-01	PT 77-82	128	3.17E-02	3.14E-02
PG-2	2	-2.00E-01	-2.02E-01	PT 82-83	129	4.76E-01	4.83E-01
PG-3	3	-3.90E-01	-3.85E-01	PT 83-84	130	2.53E-01	2.56E-01
PG-4	4	-3.90E-01	-3.96E-01	PT 83-85	131	4.37E-01	4.38E-01
PG-5	5	0.00E+00	0.00E+00	PT 84-85	132	3.68E-01	3.75E-01
PG-6	6	-5.20E-01	-5.19E-01	PT 85-86	133	-1.71E-01	-1.73E-01
PG-7	7	-1.90E-01	-1.94E-01	PT 86-87	134	4.00E-02	3.98E-02
PG-8	8	-2.80E-01	-2.82E-01	PT 85-88	135	5.09E-01	5.09E-01
PG-9	9	0.00E+00	0.00E+00	PT 85-89	136	7.25E-01	7.30E-01
PG-10	10	4.50E+00	4.47E+00	PT 88-89	137	1.00E+00	1.01E+00
PG-11	11	-7.00E-01	-6.94E-01	PT 89-90	138	-5.65E-01	-5.64E-01
PG-12	12	3.80E-01	3.85E-01	PT 89-90	139	-1.08E+0	-1.09E+00
PG-13	13	-3.40E-01	-3.38E-01	PT 90-91	140	-1.40E-02	-1.39E-02
PG-14	14	-1.40E-01	-1.38E-01	PT 89-92	141	-1.98E+0	-1.94E+00
PG-15	15	-9.00E-01	-8.95E-01	PT 89-92	142	-6.20E-01	-6.28E-01
PG-16	16	-2.50E-01	-2.48E-01	PT 91-92	143	8.64E-02	8.53E-02
PG-17	17	-1.10E-01	-1.08E-01	PT 92-93	144	-5.67E-01	-5.76E-01
PG-18	18	-6.00E-01	-6.05E-01	PT 92-94	145	-5.07E-01	-5.02E-01
PG-19	19	-4.50E-01	-4.51E-01	PT 93-94	146	-4.42E-01	-4.44E-01
PG-20	20	-1.80E-01	-1.78E-01	PT 94-95	147	-4.06E-01	-4.04E-01
PG-21	21	-1.40E-01	-1.39E-01	PT 80-96	148	-1.87E-01	-1.89E-01
PG-22	22	-1.00E-01	-1.01E-01	PT 82-96	149	9.96E-02	1.01E-01
PG-23	23	-7.00E-02	-6.91E-02	PT 94-96	150	-1.97E-01	-1.95E-01
PG-24	24	-1.30E-01	-1.32E-01	PT 80-97	151	-2.62E-01	-2.58E-01
PG-25	25	2.20E+00	2.24E+00	PT 80-98	152	-2.87E-01	-2.84E-01
PG-26	26	3.14E+00	3.10E+00	PT 80-99	153	-1.94E-01	-1.95E-01
PG-27	27	-7.10E-01	-7.01E-01	PT 92-100	154	-3.07E-01	-3.13E-01
PG-28	28	-1.70E-01	-1.70E-01	PT 94-100	155	-3.87E-02	-3.90E-02
PG-29	29	-2.40E-01	-2.38E-01	PT 95-96	156	1.45E-02	1.48E-02

PG-30	30	0.00E+00	0.00E+00	PT 96-97	157	1.12E-01	1.12E-01
PG-31	31	-3.60E-01	-3.66E-01	PT 98-100	158	5.28E-02	5.30E-02
PG-32	32	-5.90E-01	-5.92E-01	PT 99-100	159	2.27E-01	2.24E-01
PG-33	33	-2.30E-01	-2.31E-01	PT 100-101	160	1.70E-01	1.73E-01
PG-34	34	-5.90E-01	-5.96E-01	PT 92-102	161	-4.44E-01	-4.43E-01
PG-35	35	-3.30E-01	-3.30E-01	PT 101-102	162	3.94E-01	3.99E-01
PG-36	36	-3.10E-01	-3.04E-01	PT 100-103	163	-1.19E+00	-1.19E+00
PG-37	37	0.00E+00	0.00E+00	PT 100-104	164	-5.47E-01	-5.52E-01
PG-38	38	0.00E+00	0.00E+00	PT 103-104	165	-3.19E-01	-3.23E-01
PG-39	39	-2.70E-01	-2.69E-01	PT 103-105	166	-4.22E-01	-4.17E-01
PG-40	40	-6.60E-01	-6.69E-01	PT 100-106	167	-5.81E-01	-5.74E-01
PG-41	41	-3.70E-01	-3.74E-01	PT 104-105	168	-4.83E-01	-4.85E-01
PG-42	42	-9.60E-01	-9.69E-01	PT 105-105	169	-8.85E-02	-8.75E-02
PG-43	43	-1.80E-01	-1.79E-01	PT 105-107	170	-2.63E-01	-2.67E-01
PG-44	44	-1.60E-01	-1.58E-01	PT 105-108	171	-2.38E-01	-2.41E-01
PG-45	45	-5.30E-01	-5.20E-01	PT 106-107	172	-2.37E-01	-2.38E-01
PG-46	46	-9.00E-02	-8.84E-02	PT 108-109	173	-2.17E-01	-2.14E-01
PG-47	47	-3.40E-01	-3.46E-01	PT 103-110	174	-5.91E-01	-5.90E-01
PG-48	48	-2.00E-01	-1.98E-01	PT 109-110	175	-1.36E-01	-1.36E-01
PG-49	49	1.17E+00	1.16E+00	PT 110-111	176	3.60E-01	3.54E-01
PG-50	50	-1.70E-01	-1.71E-01	PT 110-112	177	-6.80E-01	-6.69E-01
PG-51	51	-1.70E-01	-1.73E-01	PT 17-113	178	-2.05E-02	-2.02E-02
PG-52	52	-1.80E-01	-1.81E-01	PT 32-113	179	-3.95E-02	-3.90E-02
PG-53	53	-2.30E-01	-2.32E-01	PT 32-114	180	-9.36E-02	-9.34E-02
PG-54	54	-6.50E-01	-6.48E-01	PT 27-115	181	-2.06E-01	-2.10E-01
PG-55	55	-6.30E-01	-6.40E-01	PT 114-115	182	-1.36E-02	-1.33E-02
PG-56	56	-8.40E-01	-8.38E-01	PT 68-116	183	-1.84E+00	-1.83E+00
PG-57	57	-1.20E-01	-1.21E-01	PT 12-117	184	-2.00E-01	-2.03E-01
PG-58	58	-1.20E-01	-1.21E-01	PT 75-118	185	-3.99E-01	-4.04E-01
PG-59	59	-1.22E+00	-1.21E+00	PT 76-118	186	6.87E-02	6.81E-02
PG-60	60	-7.80E-01	-7.88E-01	QF 1-2	1	-1.30E-01	-1.27E-01

PG-61	61	1.60E+00	1.59E+00	QF 1-3	2	-1.71E-01	-1.67E-01
PG-62	62	-7.70E-01	-7.84E-01	QF 4-5	3	-2.68E-01	-2.78E-01
PG-63	63	0.00E+00	0.00E+00	QF 3-5	4	-1.45E-01	-1.48E-01
PG-64	64	0.00E+00	0.00E+00	QF 5-6	5	4.11E-02	4.15E-02
PG-65	65	3.91E+00	3.92E+00	QF 6-7	6	-4.77E-02	-4.93E-02
PG-66	66	3.53E+00	3.57E+00	QF 8-9	7	-8.97E-01	-8.98E-01
PG-67	67	-2.80E-01	-2.74E-01	QF 8-5	8	1.25E+00	1.29E+00
PG-68	68	0.00E+00	0.00E+00	QF 9-10	9	-2.44E-01	-2.44E-01
PG-69	69	5.14E+00	5.20E+00	QF 4-11	10	-2.18E-03	-2.14E-03
PG-70	70	-6.60E-01	-6.50E-01	QF 5-11	11	2.97E-02	2.90E-02
PG-71	71	0.00E+00	0.00E+00	QF 11-12	12	-3.51E-01	-3.55E-01
PG-72	72	-1.20E-01	-1.18E-01	QF 2-12	13	-2.00E-01	-2.07E-01
PG-73	73	-6.00E-02	-5.91E-02	QF 3-12	14	-1.24E-01	-1.21E-01
PG-74	74	-6.80E-01	-6.72E-01	QF 7-12	15	-6.51E-02	-6.64E-02
PG-75	75	-4.70E-01	-4.75E-01	QF 11-13	16	1.14E-01	1.18E-01
PG-76	76	-6.80E-01	-6.80E-01	QF 12-14	17	2.62E-02	2.61E-02
PG-77	77	-6.10E-01	-6.01E-01	QF 13-15	18	-3.84E-02	-3.92E-02
PG-78	78	-7.10E-01	-7.17E-01	QF 14-15	19	3.14E-02	3.23E-02
PG-79	79	-3.90E-01	-3.95E-01	QF 12-16	20	4.30E-02	4.33E-02
PG-80	80	3.47E+00	3.46E+00	QF 15-17	21	-2.43E-01	-2.38E-01
PG-81	81	0.00E+00	0.00E+00	QF 16-17	22	-3.68E-02	-3.54E-02
PG-82	82	-5.40E-01	-5.35E-01	QF 17-18	23	2.48E-01	2.40E-01
PG-83	83	-2.00E-01	-2.02E-01	QF 18-19	24	1.68E-01	1.73E-01
PG-84	84	-1.10E-01	-1.12E-01	QF 19-20	25	5.17E-02	5.00E-02
PG-85	85	-2.40E-01	-2.38E-01	QF 15-19	26	1.57E-01	1.63E-01
PG-86	86	-2.10E-01	-2.10E-01	QF 20-21	27	4.71E-02	4.71E-02
PG-87	87	4.00E-02	3.94E-02	QF 21-22	28	-2.10E-02	-2.14E-02
PG-88	88	-4.80E-01	-4.73E-01	QF 22-23	29	-6.76E-02	-6.77E-02
PG-89	89	6.07E+00	5.95E+00	QF 23-24	30	1.04E-01	1.06E-01
PG-90	90	-1.63E+00	-1.64E+00	QF 23-25	31	-2.62E-01	-2.62E-01
PG-91	91	-1.00E-01	-9.92E-02	QF 26-25	32	2.16E-01	2.12E-01
PG-92	92	-6.50E-01	-6.44E-01	QF 25-27	33	3.01E-01	2.99E-01
PG-93	93	-1.20E-01	-1.20E-01	QF 27-28	34	-5.92E-03	-6.00E-03
PG-94	94	-3.00E-01	-3.02E-01	QF 28-29	35	-6.57E-02	-6.39E-02
PG-95	95	-4.20E-01	-4.23E-01	QF 30-17	36	9.30E-01	9.58E-01
PG-96	96	-3.80E-01	-3.75E-01	QF 8-30	37	2.81E-01	2.84E-01
PG-97	97	-1.50E-01	-1.48E-01	QF 26-30	38	-1.15E-01	-1.18E-01
PG-98	98	-3.40E-01	-3.43E-01	QF 17-31	39	1.15E-01	1.14E-01
PG-99	99	-4.20E-01	-4.24E-01	QF 29-31	40	-8.64E-02	-8.60E-02
PG-100	100	2.15E+00	2.14E+00	QF 23-32	41	5.05E-02	4.96E-02
PG-101	101	-2.20E-01	-2.23E-01	QF 31-32	42	1.24E-01	1.21E-01
PG-102	102	-5.00E-02	-4.91E-02	QF 27-32	43	1.76E-02	1.77E-02
PG-103	103	1.70E-01	1.67E-01	QF 15-33	44	-4.42E-02	-4.54E-02
PG-104	104	-3.80E-01	-3.73E-01	QF 19-34	45	-1.04E-01	-1.04E-01
PG-105	105	-3.10E-01	-3.09E-01	QF 35-36	46	4.04E-02	4.00E-02
PG-106	106	-4.30E-01	-4.26E-01	QF 35-37	47	-1.30E-01	-1.35E-01
PG-107	107	-5.00E-01	-4.98E-01	QF 33-37	48	-1.05E-01	-1.08E-01

PG-108	108	-2.00E-02	-2.00E-02	QF 34-36	49	4.70E-02	4.86E-02
PG-109	109	-8.00E-02	-7.92E-02	QF 34-37	50	-4.42E-01	-4.53E-01
PG-110	110	-3.90E-01	-3.97E-01	QF 38-37	51	1.14E+00	1.18E+00
PG-111	111	3.60E-01	3.57E-01	QF 37-39	52	2.98E-02	2.96E-02
PG-112	112	-6.80E-01	-6.72E-01	QF 37-40	53	-3.68E-02	-3.80E-02
PG-113	113	-6.00E-02	-6.02E-02	QF 30-38	54	1.90E-01	1.84E-01
PG-114	114	-8.00E-02	-8.08E-02	QF 39-40	55	-8.70E-02	-8.99E-02
PG-115	115	-2.20E-01	-2.21E-01	QF 40-41	56	1.19E-02	1.16E-02
PG-116	116	-1.84E+00	-1.87E+00	QF 40-42	57	-6.45E-02	-6.64E-02
PG-117	117	-2.00E-01	-2.00E-01	QF 41-42	58	-7.79E-02	-7.62E-02
PG-118	118	-3.30E-01	-3.32E-01	QF 43-44	59	-1.33E-02	-1.36E-02
QG-1	1	-3.01E-01	-3.03E-01	QF 34-43	60	1.63E-02	1.69E-02
QG-2	2	-9.00E-02	-8.91E-02	QF 44-45	61	5.48E-02	5.49E-02
QG-3	3	-1.00E-01	-1.03E-01	QF 45-46	62	-3.57E-02	-3.57E-02
QG-4	4	-2.70E-01	-2.76E-01	QF 46-47	63	-1.22E-02	-1.27E-02
QG-5	5	0.00E+00	0.00E+00	QF 46-48	64	-5.83E-02	-5.61E-02
QG-6	6	-6.07E-02	-6.00E-02	QF 47-49	65	-1.08E-01	-1.12E-01
QG-7	7	-2.00E-02	-1.97E-02	QF 42-49	66	5.24E-02	5.04E-02
QG-8	8	6.31E-01	6.28E-01	QF 42-49	67	5.24E-02	5.32E-02
QG-9	9	0.00E+00	0.00E+00	QF 45-49	68	-2.08E-02	-2.09E-02
QG-10	10	-5.10E-01	-5.05E-01	QF 48-49	69	3.21E-02	3.10E-02
QG-11	11	-2.30E-01	-2.24E-01	QF 49-50	70	1.34E-01	1.38E-01
QG-12	12	8.13E-01	8.38E-01	QF 49-51	71	2.04E-01	1.98E-01
QG-13	13	-1.60E-01	-1.64E-01	QF 51-52	72	6.25E-02	6.19E-02
QG-14	14	-1.00E-02	-1.01E-02	QF 52-53	73	1.99E-02	1.98E-02
QG-15	15	-2.28E-01	-2.33E-01	QF 53-54	74	-5.55E-02	-5.38E-02
QG-16	16	-1.00E-01	-1.03E-01	QF 49-54	75	1.31E-01	1.27E-01
QG-17	17	-3.00E-02	-2.94E-02	QF 49-54	76	1.12E-01	1.09E-01
QG-18	18	-5.57E-02	-5.64E-02	QF 54-55	77	1.46E-02	1.47E-02
QG-19	19	-3.93E-01	-4.08E-01	QF 54-56	78	4.35E-02	4.22E-02
QG-20	20	-3.00E-02	-3.01E-02	QF 55-56	79	-5.82E-02	-6.00E-02
QG-21	21	-8.00E-02	-8.13E-02	QF 56-57	80	-9.10E-02	-9.38E-02
QG-22	22	-5.00E-02	-5.08E-02	QF 50-57	81	9.14E-02	8.78E-02
QG-23	23	-3.00E-02	-3.06E-02	QF 56-58	82	-3.69E-02	-3.67E-02
QG-24	24	-1.49E-01	-1.52E-01	QF 51-58	83	3.16E-02	3.13E-02
QG-25	25	5.00E-01	5.17E-01	QF 54-59	84	-7.51E-02	-7.45E-02
QG-26	26	1.01E-01	1.00E-01	QF 56-59	85	-4.17E-02	-4.19E-02
QG-27	27	-9.02E-02	-8.79E-02	QF 56-59	86	-3.91E-02	-3.99E-02
QG-28	28	-7.00E-02	-6.74E-02	QF 55-59	87	-8.26E-02	-8.13E-02
QG-29	29	-4.00E-02	-3.86E-02	QF 59-60	88	3.57E-02	3.64E-02
QG-30	30	0.00E+00	0.00E+00	QF 59-61	89	5.03E-02	4.99E-02
QG-31	31	5.59E-02	5.79E-02	QF 60-61	90	8.52E-02	8.25E-02
QG-32	32	-3.93E-01	-3.84E-01	QF 60-62	91	-7.11E-02	-7.36E-02
QG-33	33	-9.00E-02	-8.83E-02	QF 61-62	92	-1.39E-01	-1.36E-01
QG-34	34	-4.68E-01	-4.66E-01	QF 63-59	93	6.75E-01	6.94E-01
QG-35	35	-9.00E-02	-9.09E-02	QF 63-64	94	-6.75E-01	-6.74E-01
QG-36	36	-9.27E-02	-9.59E-02	QF 64-61	95	1.40E-01	1.42E-01

QG-37	37	0.00E+00	0.00E+00	QF 38-65	96	-5.76E-01	-5.77E-01
QG-38	38	0.00E+00	0.00E+00	QF 64-65	97	-6.65E-01	-6.71E-01
QG-39	39	-1.10E-01	-1.06E-01	QF 49-66	98	4.33E-02	4.31E-02
QG-40	40	5.45E-02	5.26E-02	QF 49-66	99	4.33E-02	4.32E-02
QG-41	41	-1.00E-01	-1.01E-01	QF 62-66	100	-1.73E-01	-1.69E-01
QG-42	42	1.80E-01	1.82E-01	QF 62-67	101	-1.44E-01	-1.48E-01
QG-43	43	-7.00E-02	-6.74E-02	QF 65-66	102	7.22E-01	7.44E-01
QG-44	44	-8.00E-02	-7.80E-02	QF 66-67	103	1.93E-01	1.94E-01
QG-45	45	-2.20E-01	-2.14E-01	QF 65-68	104	-2.24E-01	-2.25E-01
QG-46	46	-1.50E-01	-1.52E-01	QF 47-69	105	1.16E-01	1.17E-01
QG-47	47	0.00E+00	0.00E+00	QF 49-69	106	1.06E-01	1.08E-01
QG-48	48	-1.10E-01	-1.12E-01	QF 68-69	107	1.13E+00	1.14E+00
QG-49	49	8.58E-01	8.28E-01	QF 69-70	108	1.61E-01	1.58E-01
QG-50	50	-4.00E-02	-4.09E-02	QF 24-70	109	-2.97E-02	-3.04E-02
QG-51	51	-8.00E-02	-8.07E-02	QF 70-71	110	-1.24E-01	-1.24E-01
QG-52	52	-5.00E-02	-4.87E-02	QF 24-72	111	3.31E-02	3.31E-02
QG-53	53	-1.10E-01	-1.08E-01	QF 71-72	112	-9.40E-03	-9.35E-03
QG-54	54	-2.81E-01	-2.78E-01	QF 71-73	113	-1.07E-01	-1.07E-01
QG-55	55	-1.73E-01	-1.74E-01	QF 70-74	114	1.29E-01	1.30E-01
QG-56	56	-2.03E-01	-2.10E-01	QF 70-75	115	9.94E-02	9.98E-02
QG-57	57	-3.00E-02	-2.96E-02	QF 69-75	116	2.05E-01	2.12E-01
QG-58	58	-3.00E-02	-2.99E-02	QF 74-75	117	-6.19E-02	-6.04E-02
QG-59	59	-3.62E-01	-3.76E-01	QF 76-77	118	-2.10E-01	-2.10E-01
QG-60	60	-3.00E-02	-2.91E-02	QF 69-77	119	6.78E-02	6.62E-02
QG-61	61	-4.04E-01	-3.93E-01	QF 75-77	120	-9.55E-02	-9.59E-02
QG-62	62	-1.27E-01	-1.29E-01	QF 77-78	121	6.61E-02	6.48E-02
QG-63	63	0.00E+00	0.00E+00	QF 78-79	122	-1.84E-01	-1.82E-01
QG-64	64	0.00E+00	0.00E+00	QF 77-80	123	-3.74E-01	-3.74E-01
QG-65	65	8.15E-01	8.32E-01	QF 77-80	124	-2.05E-01	-2.11E-01
QG-66	66	-2.00E-01	-2.03E-01	QF 79-80	125	-2.96E-01	-2.92E-01
QG-67	67	-7.00E-02	-7.22E-02	QF 68-81	126	-4.61E-02	-4.53E-02
QG-68	68	0.00E+00	0.00E+00	QF 81-80	127	7.55E-01	7.38E-01
QG-69	69	-8.24E-01	-8.07E-01	QF 77-82	128	1.76E-01	1.76E-01
QG-70	70	-1.03E-01	-1.05E-01	QF 82-83	129	2.44E-01	2.35E-01
QG-71	71	0.00E+00	0.00E+00	QF 83-84	130	1.47E-01	1.52E-01
QG-72	72	-1.11E-01	-1.08E-01	QF 83-85	131	1.20E-01	1.24E-01
QG-73	73	9.65E-02	9.62E-02	QF 84-85	132	8.99E-02	8.95E-02
QG-74	74	-3.26E-01	-3.27E-01	QF 85-86	133	-7.35E-02	-7.27E-02
QG-75	75	-1.10E-01	-1.13E-01	QF 86-87	134	-1.51E-01	-1.56E-01
QG-76	76	-3.07E-01	-3.04E-01	QF 85-88	135	7.60E-02	7.31E-02
QG-77	77	-1.58E-01	-1.63E-01	QF 85-89	136	6.77E-03	6.84E-03
QG-78	78	-2.60E-01	-2.60E-01	QF 88-89	137	-2.47E-02	-2.50E-02
QG-79	79	-3.20E-01	-3.17E-01	QF 89-90	138	-4.72E-02	-4.56E-02
QG-80	80	7.95E-01	8.01E-01	QF 89-90	139	-5.44E-02	-5.34E-02
QG-81	81	0.00E+00	0.00E+00	QF 90-91	140	4.42E-02	4.48E-02
QG-82	82	-2.70E-01	-2.69E-01	QF 89-92	141	-2.10E-02	-2.18E-02
QG-83	83	-1.00E-01	-9.72E-02	QF 89-92	142	-5.07E-02	-5.08E-02

QG-84	84	-7.00E-02	-6.94E-02	QF 91-92	143	-6.63E-02	-6.63E-02
QG-85	85	-2.06E-01	-2.07E-01	QF 92-93	144	-1.17E-01	-1.14E-01
QG-86	86	-1.00E-01	-9.89E-02	QF 92-94	145	-1.52E-01	-1.54E-01
QG-87	87	1.10E-01	1.10E-01	QF 93-94	146	-1.95E-01	-1.97E-01
QG-88	88	-1.00E-01	-9.67E-02	QF 94-95	147	9.01E-02	9.34E-02
QG-89	89	-5.90E-02	-5.84E-02	QF 80-96	148	2.11E-01	2.08E-01
QG-90	90	1.73E-01	1.75E-01	QF 82-96	149	-6.57E-02	-6.48E-02
QG-91	91	-1.31E-01	-1.34E-01	QF 94-96	150	-9.82E-02	-9.89E-02
QG-92	92	-2.40E-01	-2.31E-01	QF 80-97	151	2.58E-01	2.56E-01
QG-93	93	-7.00E-02	-6.92E-02	QF 80-98	152	8.32E-02	8.63E-02
QG-94	94	-1.60E-01	-1.62E-01	QF 80-99	153	8.17E-02	8.43E-02
QG-95	95	-3.10E-01	-3.03E-01	QF 92-100	154	-1.65E-01	-1.71E-01
QG-96	96	-1.50E-01	-1.48E-01	QF 94-100	155	-5.05E-01	-5.08E-01
QG-97	97	-9.00E-02	-9.31E-02	QF 95-96	156	-2.17E-01	-2.19E-01
QG-98	98	-8.00E-02	-8.25E-02	QF 96-97	157	-2.02E-01	-2.09E-01
QG-99	99	-1.75E-01	-1.68E-01	QF 98-100	158	2.43E-02	2.38E-02
QG-100	100	7.76E-01	7.91E-01	QF 99-100	159	-4.59E-02	-4.67E-02
QG-101	101	-1.50E-01	-1.46E-01	QF 100-101	160	2.29E-01	2.32E-01
QG-102	102	-3.00E-02	-2.98E-02	QF 92-102	161	-8.39E-02	-8.51E-02
QG-103	103	5.94E-01	5.83E-01	QF 101-102	162	1.01E-01	1.03E-01
QG-104	104	-2.26E-01	-2.25E-01	QF 100-103	163	-2.21E-01	-2.17E-01
QG-105	105	-4.43E-01	-4.47E-01	QF 100-104	164	1.06E-01	1.05E-01
QG-106	106	-1.60E-01	-1.58E-01	QF 103-104	165	1.39E-01	1.34E-01
QG-107	107	-5.44E-02	-5.30E-02	QF 103-105	166	1.28E-01	1.32E-01
QG-108	108	-1.00E-02	-1.00E-02	QF 100-106	167	9.48E-02	9.13E-02
QG-109	109	-3.00E-02	-2.91E-02	QF 104-105	168	2.63E-02	2.59E-02
QG-110	110	-2.97E-01	-2.86E-01	QF 105-105	169	3.88E-02	3.87E-02
QG-111	111	-1.84E-02	-1.86E-02	QF 105-107	170	-2.37E-02	-2.42E-02
QG-112	112	2.85E-01	2.81E-01	QF 105-108	171	-1.11E-01	-1.07E-01
QG-113	113	6.75E-02	6.95E-02	QF 106-107	172	-3.73E-02	-3.61E-02
QG-114	114	-3.00E-02	-2.97E-02	QF 108-109	173	-1.09E-01	-1.13E-01
QG-115	115	-7.00E-02	-7.25E-02	QF 103-110	174	8.35E-02	8.04E-02
QG-116	116	5.13E-01	4.98E-01	QF 109-110	175	-1.34E-01	-1.39E-01
QG-117	117	-8.00E-02	-8.00E-02	QF 110-111	176	9.56E-03	9.67E-03

QG-118	118	-1.50E-01	-1.54E-01	QF 110-112	177	-3.06E-01	-2.98E-01
PF 1-2	1	-1.24E-01	-1.25E-01	QF 17-113	178	5.90E-02	5.66E-02
PF 1-3	2	-3.86E-01	-3.79E-01	QF 32-113	179	-1.78E-01	-1.74E-01
PF 4-5	3	-1.03E+00	-1.02E+00	QF 32-114	180	1.78E-02	1.74E-02
PF 3-5	4	-6.81E-01	-6.75E-01	QF 27-115	181	5.06E-02	5.16E-02
PF 5-6	5	8.85E-01	8.77E-01	QF 114-115	182	2.21E-03	2.15E-03
PF 6-7	6	3.55E-01	3.61E-01	QF 68-116	183	-6.64E-01	-6.62E-01
PF 8-9	7	-4.41E+00	-4.36E+00	QF 12-117	184	5.20E-02	5.29E-02
PF 8-5	8	3.38E+00	3.35E+00	QF 75-118	185	2.36E-01	2.42E-01
PF 9-10	9	-4.45E+00	-4.44E+00	QF 76-118	186	-9.69E-02	-9.95E-02
PF 4-11	10	6.42E-01	6.42E-01	QT 1-2	1	1.10E-01	1.13E-01
PF 5-11	11	7.72E-01	7.81E-01	QT 1-3	2	1.69E-01	1.62E-01
PF 11-12	12	3.43E-01	3.46E-01	QT 4-5	3	2.75E-01	2.67E-01
PF 2-12	13	-3.25E-01	-3.31E-01	QT 3-5	4	1.73E-01	1.70E-01
PF 3-12	14	-9.79E-02	-9.97E-02	QT 5-6	5	-1.30E-02	-1.35E-02
PF 7-12	15	1.65E-01	1.62E-01	QT 6-7	6	4.51E-02	4.58E-02
PF 11-13	16	3.51E-01	3.49E-01	QT 8-9	7	2.44E-01	2.35E-01
PF 12-14	17	1.83E-01	1.84E-01	QT 8-5	8	-9.20E-01	-9.26E-01
PF 13-15	18	7.68E-03	7.64E-03	QT 9-10	9	-5.10E-01	-5.17E-01
PF 14-15	19	4.24E-02	4.22E-02	QT 4-11	10	1.35E-02	1.33E-02
PF 12-16	20	7.51E-02	7.63E-02	QT 5-11	11	-6.21E-03	-6.30E-03
PF 15-17	21	-1.04E+00	-1.04E+00	QT 11-12	12	3.51E-01	3.38E-01
PF 16-17	22	-1.75E-01	-1.72E-01	QT 2-12	13	1.94E-01	1.97E-01
PF 17-18	23	8.03E-01	8.07E-01	QT 3-12	14	8.86E-02	8.79E-02
PF 18-19	24	1.94E-01	1.93E-01	QT 7-12	15	5.76E-02	5.88E-02
PF 19-20	25	-1.06E-01	-1.06E-01	QT 11-13	16	-1.22E-01	-1.26E-01
PF 15-19	26	1.15E-01	1.16E-01	QT 12-14	17	-4.14E-02	-4.04E-02
PF 20-21	27	-2.87E-01	-2.92E-01	QT 13-15	18	-2.04E-02	-2.02E-02
PF 21-22	28	-4.28E-01	-4.37E-01	QT 14-15	19	-7.83E-02	-7.64E-02
PF 22-23	29	-5.33E-01	-5.27E-01	QT 12-16	20	-6.32E-02	-6.19E-02
PF 23-24	30	8.28E-02	8.28E-02	QT 15-17	21	2.52E-01	2.55E-01
PF 23-25	31	-1.63E+00	-1.64E+00	QT 16-17	22	-3.04E-03	-3.00E-03
PF 26-25	32	9.03E-01	8.92E-01	QT 17-18	23	-2.24E-01	-2.29E-01
PF 25-27	33	1.44E+00	1.45E+00	QT 18-19	24	-1.75E-01	-1.72E-01
PF 27-28	34	3.29E-01	3.34E-01	QT 19-20	25	-7.71E-02	-7.75E-02
PF 28-29	35	1.57E-01	1.56E-01	QT 15-19	26	-1.65E-01	-1.61E-01
PF 30-17	36	2.31E+00	2.27E+00	QT 20-21	27	-5.90E-02	-5.78E-02
PF 8-30	37	7.42E-01	7.54E-01	QT 21-22	28	1.76E-02	1.79E-02
PF 26-30	38	2.24E+00	2.24E+00	QT 22-23	29	7.69E-02	7.49E-02
PF 17-31	39	1.48E-01	1.47E-01	QT 23-24	30	-1.52E-01	-1.54E-01
PF 29-31	40	-8.42E-02	-8.54E-02	QT 23-25	31	3.86E-01	3.79E-01
PF 23-32	41	9.30E-01	9.36E-01	QT 26-25	32	-1.86E-01	-1.92E-01
PF 31-32	42	-2.99E-01	-2.97E-01	QT 25-27	33	-1.53E-01	-1.48E-01
PF 27-32	43	1.25E-01	1.25E-01	QT 27-28	34	-4.32E-03	-4.42E-03
PF 15-33	44	7.31E-02	7.38E-02	QT 28-29	35	4.64E-02	4.76E-02
PF 19-34	45	-3.59E-02	-3.59E-02	QT 30-17	36	-7.01E-01	-6.94E-01

PF 35-36	46	8.39E-03	8.28E-03	QT 8-30	37	-7.54E-01	-7.83E-01
PF 35-37	47	-3.38E-01	-3.33E-01	QT 26-30	38	-3.66E-01	-3.66E-01
PF 33-37	48	-1.57E-01	-1.55E-01	QT 17-31	39	-1.47E-01	-1.47E-01
PF 34-36	49	3.02E-01	2.98E-01	QT 29-31	40	7.92E-02	8.03E-02
PF 34-37	50	-9.43E-01	-9.48E-01	QT 23-32	41	-6.24E-02	-6.17E-02
PF 38-37	51	2.43E+00	2.43E+00	QT 31-32	42	-1.36E-01	-1.40E-01
PF 37-39	52	5.49E-01	5.43E-01	QT 27-32	43	-3.43E-02	-3.49E-02
PF 37-40	53	4.40E-01	4.32E-01	QT 15-33	44	1.49E-02	1.48E-02
PF 30-38	54	6.24E-01	6.30E-01	QT 19-34	45	4.60E-02	4.52E-02
PF 39-40	55	2.69E-01	2.71E-01	QT 35-36	46	-4.29E-02	-4.22E-02
PF 40-41	56	1.54E-01	1.57E-01	QT 35-37	47	1.24E-01	1.22E-01
PF 40-42	57	-1.18E-01	-1.17E-01	QT 33-37	48	7.46E-02	7.68E-02
PF 41-42	58	-2.16E-01	-2.19E-01	QT 34-36	49	-4.98E-02	-4.81E-02
PF 43-44	59	-1.66E-01	-1.66E-01	QT 34-37	50	4.43E-01	4.31E-01
PF 34-43	60	1.41E-02	1.40E-02	QT 38-37	51	-8.80E-01	-9.04E-01
PF 44-45	61	-3.28E-01	-3.33E-01	QT 37-39	52	-2.30E-02	-2.31E-02
PF 45-46	62	-3.63E-01	-3.62E-01	QT 37-40	53	2.96E-02	2.90E-02
PF 46-47	63	-3.11E-01	-3.10E-01	QT 30-38	54	-5.60E-01	-5.40E-01
PF 46-48	64	-1.48E-01	-1.47E-01	QT 39-40	55	7.75E-02	7.61E-02
PF 47-49	65	-9.54E-02	-9.47E-02	QT 40-41	56	-2.21E-02	-2.21E-02
PF 42-49	66	-6.49E-01	-6.44E-01	QT 40-42	57	2.30E-02	2.21E-02
PF 42-49	67	-6.49E-01	-6.55E-01	QT 41-42	58	5.24E-02	5.27E-02
PF 45-49	68	-4.97E-01	-4.87E-01	QT 43-44	59	-3.79E-02	-3.65E-02
PF 48-49	69	-3.49E-01	-3.55E-01	QT 34-43	60	-5.67E-02	-5.59E-02
PF 49-50	70	5.37E-01	5.46E-01	QT 44-45	61	-6.62E-02	-6.63E-02
PF 49-51	71	6.66E-01	6.70E-01	QT 45-46	62	2.12E-02	2.18E-02
PF 51-52	72	2.86E-01	2.85E-01	QT 46-47	63	-7.95E-03	-8.03E-03
PF 52-53	73	1.04E-01	1.03E-01	QT 46-48	64	1.42E-02	1.41E-02
PF 53-54	74	-1.27E-01	-1.27E-01	QT 47-49	65	9.28E-02	9.10E-02
PF 49-54	75	3.78E-01	3.71E-01	QT 42-49	66	3.70E-03	3.70E-03
PF 49-54	76	3.77E-01	3.83E-01	QT 42-49	67	3.70E-03	3.77E-03
PF 54-55	77	7.07E-02	7.14E-02	QT 45-49	68	2.31E-02	2.29E-02
PF 54-56	78	1.85E-01	1.82E-01	QT 48-49	69	-3.93E-02	-3.88E-02
PF 55-56	79	-2.14E-01	-2.12E-01	QT 49-50	70	-1.31E-01	-1.30E-01
PF 56-57	80	-2.30E-01	-2.26E-01	QT 49-51	71	-1.74E-01	-1.78E-01
PF 50-57	81	3.59E-01	3.63E-01	QT 51-52	72	-6.99E-02	-7.21E-02
PF 56-58	82	-6.67E-02	-6.78E-02	QT 52-53	73	-5.45E-02	-5.30E-02
PF 51-58	83	1.88E-01	1.89E-01	QT 53-54	74	2.99E-02	3.04E-02
PF 54-59	84	-3.04E-01	-3.05E-01	QT 49-54	75	-1.56E-01	-1.58E-01
PF 56-59	85	-2.80E-01	-2.75E-01	QT 49-54	76	-1.38E-01	-1.42E-01
PF 56-59	86	-2.93E-01	-2.90E-01	QT 54-55	77	-3.25E-02	-3.20E-02
PF 55-59	87	-3.45E-01	-3.48E-01	QT 54-56	78	-4.98E-02	-4.96E-02
PF 59-60	88	-4.33E-01	-4.37E-01	QT 55-56	79	5.57E-02	5.38E-02
PF 59-61	89	-5.17E-01	-5.16E-01	QT 56-57	80	7.49E-02	7.60E-02
PF 60-61	90	-1.12E+00	-1.14E+00	QT 50-57	81	-1.05E-01	-1.01E-01
PF 60-62	91	-9.87E-02	-1.00E-01	QT 56-58	82	1.53E-02	1.53E-02
PF 61-62	92	2.55E-01	2.54E-01	QT 51-58	83	-4.53E-02	-4.56E-02

PF 63-59	93	1.52E+00	1.50E+00	QT 54-59	84	4.26E-02	4.32E-02
PF 63-64	94	-1.52E+00	-1.53E+00	QT 56-59	85	9.87E-03	9.84E-03
PF 64-61	95	3.05E-01	3.11E-01	QT 56-59	86	1.13E-02	1.13E-02
PF 38-65	96	-1.81E+00	-1.84E+00	QT 55-59	87	5.88E-02	5.83E-02
PF 64-65	97	-1.83E+00	-1.86E+00	QT 59-60	88	-4.40E-02	-4.37E-02
PF 49-66	98	-1.32E+00	-1.31E+00	QT 59-61	89	-4.63E-02	-4.76E-02
PF 49-66	99	-1.32E+00	-1.34E+00	QT 60-61	90	-8.23E-02	-8.31E-02
PF 62-66	100	-3.72E-01	-3.76E-01	QT 60-62	91	5.74E-02	5.96E-02
PF 62-67	101	-2.43E-01	-2.39E-01	QT 61-62	92	1.32E-01	1.35E-01
PF 65-66	102	8.54E-02	8.42E-02	QT 63-59	93	-5.70E-01	-5.86E-01
PF 66-67	103	5.32E-01	5.39E-01	QT 63-64	94	5.25E-01	5.08E-01
PF 65-68	104	1.42E-01	1.44E-01	QT 64-61	95	-1.37E-01	-1.39E-01
PF 47-69	105	-5.59E-01	-5.52E-01	QT 38-65	96	-8.37E-02	-8.05E-02
PF 49-69	106	-4.65E-01	-4.70E-01	QT 64-65	97	4.01E-01	3.99E-01
PF 68-69	107	-1.26E+00	-1.27E+00	QT 49-66	98	8.32E-02	8.53E-02
PF 69-70	108	1.08E+00	1.10E+00	QT 49-66	99	8.32E-02	8.61E-02
PF 24-70	109	-6.22E-02	-6.30E-02	QT 62-66	100	1.47E-01	1.51E-01
PF 70-71	110	1.67E-01	1.69E-01	QT 62-67	101	1.21E-01	1.23E-01
PF 24-72	111	1.47E-02	1.48E-02	QT 65-66	102	-7.06E-01	-6.97E-01
PF 71-72	112	1.06E-01	1.07E-01	QT 66-67	103	-1.91E-01	-1.92E-01
PF 71-73	113	6.01E-02	5.92E-02	QT 65-68	104	-4.18E-01	-4.15E-01
PF 70-74	114	1.62E-01	1.63E-01	QT 47-69	105	-1.01E-01	-9.67E-02
PF 70-75	115	-1.33E-03	-1.32E-03	QT 49-69	106	-1.21E-01	-1.24E-01
PF 69-75	116	1.10E+00	1.10E+00	QT 68-69	107	- 1.04E+00	-1.00E+00
PF 74-75	117	-5.20E-01	-5.13E-01	QT 69-70	108	-1.40E-01	-1.42E-01
PF 76-77	118	-6.12E-01	-6.19E-01	QT 24-70	109	-6.80E-02	-7.01E-02
PF 69-77	119	6.22E-01	6.26E-01	QT 70-71	110	1.17E-01	1.15E-01
PF 75-77	120	-3.46E-01	-3.46E-01	QT 24-72	111	-7.98E-02	-7.76E-02
PF 77-78	121	4.54E-01	4.51E-01	QT 71-72	112	-3.15E-02	-3.24E-02
PF 78-79	122	-2.57E-01	-2.60E-01	QT 71-73	113	9.65E-02	9.84E-02
PF 77-80	123	-9.66E-01	-9.70E-01	QT 70-74	114	-1.54E-01	-1.60E-01
PF 77-80	124	-4.44E-01	-4.49E-01	QT 70-75	115	-1.32E-01	-1.28E-01
PF 79-80	125	-6.47E-01	-6.54E-01	QT 69-75	116	-1.83E-01	-1.81E-01
PF 68-81	126	-4.41E-01	-4.42E-01	QT 74-75	117	6.44E-02	6.50E-02
PF 81-80	127	-4.42E-01	-4.44E-01	QT 76-77	118	2.44E-01	2.39E-01
PF 77-82	128	-3.03E-02	-3.04E-02	QT 69-77	119	-1.38E-01	-1.37E-01
PF 82-83	129	-4.72E-01	-4.66E-01	QT 75-77	120	7.38E-02	7.60E-02
PF 83-84	130	-2.48E-01	-2.45E-01	QT 77-78	121	-7.63E-02	-7.47E-02
PF 83-85	131	-4.28E-01	-4.28E-01	QT 78-79	122	1.80E-01	1.85E-01
PF 84-85	132	-3.63E-01	-3.68E-01	QT 77-80	123	3.75E-01	3.75E-01
PF 85-86	133	1.72E-01	1.72E-01	QT 77-80	124	2.06E-01	2.05E-01
PF 86-87	134	-3.95E-02	-3.92E-02	QT 79-80	125	3.11E-01	2.99E-01
PF 85-88	135	-5.04E-01	-4.94E-01	QT 68-81	126	-7.55E-01	-7.36E-01
PF 85-89	136	-7.12E-01	-7.22E-01	QT 81-80	127	-7.30E-01	-7.29E-01
PF 88-89	137	-9.89E-01	-9.96E-01	QT 77-82	128	-2.53E-01	-2.44E-01
PF 89-90	138	5.82E-01	5.85E-01	QT 82-83	129	-2.70E-01	-2.70E-01
PF 89-90	139	1.11E+00	1.11E+00	QT 83-84	130	-1.60E-01	-1.60E-01

PF 90-91	140	1.41E-02	1.44E-02	QT 83-85	131	-1.23E-01	-1.28E-01
PF 89-92	141	2.02E+00	1.98E+00	QT 84-85	132	-9.24E-02	-9.38E-02
PF 89-92	142	6.36E-01	6.33E-01	QT 85-86	133	5.09E-02	4.97E-02
PF 91-92	143	-8.60E-02	-8.50E-02	QT 86-87	134	1.10E-01	1.11E-01
PF 92-93	144	5.76E-01	5.73E-01	QT 85-88	135	-7.53E-02	-7.42E-02
PF 92-94	145	5.22E-01	5.26E-01	QT 85-89	136	3.73E-02	3.79E-02
PF 93-94	146	4.47E-01	4.49E-01	QT 88-89	137	7.70E-02	7.56E-02
PF 94-95	147	4.09E-01	4.12E-01	QT 89-90	138	5.81E-02	5.79E-02
PF 80-96	148	1.90E-01	1.91E-01	QT 89-90	139	7.07E-02	7.25E-02
PF 82-96	149	-9.94E-02	-9.79E-02	QT 90-91	140	-6.46E-02	-6.27E-02
PF 94-96	150	1.98E-01	1.97E-01	QT 89-92	141	1.70E-01	1.72E-01
PF 80-97	151	2.64E-01	2.62E-01	QT 89-92	142	7.29E-02	7.54E-02
PF 80-98	152	2.89E-01	2.87E-01	QT 91-92	143	3.59E-02	3.49E-02
PF 80-99	153	1.96E-01	1.94E-01	QT 92-93	144	1.25E-01	1.30E-01
PF 92-100	154	3.15E-01	3.21E-01	QT 92-94	145	1.59E-01	1.63E-01
PF 94-100	155	4.28E-02	4.21E-02	QT 93-94	146	1.94E-01	1.99E-01
PF 95-96	156	-1.38E-02	-1.36E-02	QT 94-95	147	-9.31E-02	-8.96E-02
PF 96-97	157	-1.11E-01	-1.11E-01	QT 80-96	148	-2.46E-01	-2.55E-01
PF 98-100	158	-5.26E-02	-5.17E-02	QT 82-96	149	1.29E-02	1.26E-02
PF 99-100	159	-2.26E-01	-2.23E-01	QT 94-96	150	7.98E-02	7.99E-02
PF 100-101	160	-1.67E-01	-1.70E-01	QT 80-97	151	-2.72E-01	-2.69E-01
PF 92-102	161	4.47E-01	4.38E-01	QT 80-98	152	-1.04E-01	-1.04E-01
PF 101-102	162	-3.90E-01	-3.88E-01	QT 80-99	153	-1.29E-01	-1.33E-01
PF 100-103	163	1.22E+00	1.21E+00	QT 92-100	154	1.54E-01	1.53E-01
PF 100-104	164	5.62E-01	5.61E-01	QT 94-100	155	4.58E-01	4.46E-01
PF 103-104	165	3.25E-01	3.27E-01	QT 95-96	156	2.05E-01	2.01E-01
PF 103-105	166	4.34E-01	4.28E-01	QT 96-97	157	1.82E-01	1.88E-01
PF 100-106	167	6.04E-01	5.93E-01	QT 98-100	158	-7.30E-02	-7.13E-02
PF 104-105	168	4.86E-01	4.93E-01	QT 99-100	159	2.79E-02	2.87E-02
PF 105-105	169	8.86E-02	8.84E-02	QT 100-101	160	-2.51E-01	-2.44E-01
PF 105-107	170	2.68E-01	2.64E-01	QT 92-102	161	8.13E-02	8.03E-02
PF 105-108	171	2.40E-01	2.40E-01	QT 101-102	162	-1.11E-01	-1.10E-01
PF 106-107	172	2.40E-01	2.39E-01	QT 100-103	163	2.44E-01	2.37E-01
PF 108-109	173	2.18E-01	2.15E-01	QT 100-104	164	-9.41E-02	-9.54E-02
PF 103-110	174	6.06E-01	6.01E-01	QT 103-104	165	-1.58E-01	-1.56E-01

PF 109-110	175	1.37E-01	1.39E-01	QT 103-105	166	-1.35E-01	-1.31E-01
PF 110-111	176	-3.57E-01	-3.58E-01	QT 100-106	167	-7.12E-02	-7.11E-02
PF 110-112	177	6.95E-01	6.85E-01	QT 104-105	168	-2.61E-02	-2.60E-02
PF 17-113	178	2.06E-02	2.06E-02	QT 105-105	169	-5.15E-02	-5.06E-02
PF 32-113	179	4.12E-02	4.12E-02	QT 105-107	170	-5.55E-03	-5.54E-03
PF 32-114	180	9.37E-02	9.44E-02	QT 105-108	171	9.92E-02	1.01E-01
PF 27-115	181	2.07E-01	2.10E-01	QT 106-107	172	5.51E-03	5.31E-03
PF 114-115	182	1.36E-02	1.38E-02	QT 108-109	173	1.04E-01	1.05E-01
PF 68-116	183	1.84E+00	1.86E+00	QT 103-110	174	-6.15E-02	-6.34E-02
PF 12-117	184	2.02E-01	2.00E-01	QT 109-110	175	1.18E-01	1.14E-01
PF 75-118	185	4.02E-01	3.95E-01	QT 110-111	176	-1.84E-02	-1.86E-02
PF 76-118	186	-6.85E-02	-6.76E-02	QT 110-112	177	2.85E-01	2.93E-01
PT 1-2	1	1.25E-01	1.25E-01	QT 17-113	178	-6.65E-02	-6.50E-02
PT 1-3	2	3.89E-01	3.84E-01	QT 32-113	179	1.34E-01	1.34E-01
PT 4-5	3	1.03E+00	1.04E+00	QT 32-114	180	-3.22E-02	-3.22E-02
PT 3-5	4	6.93E-01	6.99E-01	QT 27-115	181	-6.53E-02	-6.50E-02
PT 5-6	5	-8.75E-01	-8.74E-01	QT 114-115	182	-4.75E-03	-4.57E-03
PT 6-7	6	-3.55E-01	-3.52E-01	QT 68-116	183	5.13E-01	4.93E-01
PT 8-9	7	4.45E+00	4.40E+00	QT 12-117	184	-8.00E-02	-7.70E-02
PT 8-5	8	-3.38E+00	-3.35E+00	QT 75-118	185	-2.36E-01	-2.43E-01
PT 9-10	9	4.50E+00	4.50E+00	QT 76-118	186	8.56E-02	8.53E-02

A.3.5. Measurement Distribution for Test Case

Table A.12 IEEE 118 Bus System – Measurement Distribution for Test Case

Type	Index	Actual	Measurement	Type	Index	Actual	Measurement
Vm-2	2	9.714E-01	9.687E-01	PF 91-92	143	-8.596E-02	-8.501E-02
Vm-3	3	9.677E-01	9.694E-01	PF 92-93	144	5.762E-01	5.728E-01
Vm-4	4	9.980E-01	9.888E-01	PF 94-95	147	4.086E-01	4.122E-01
Vm-5	5	1.002E+00	9.945E-01	PF 82-96	149	-9.944E-02	-9.785E-02
Vm-9	9	1.043E+00	1.046E+00	PF 92-100	154	3.150E-01	3.211E-01
Vm-12	12	9.900E-01	9.828E-01	PF 95-96	156	-1.376E-02	-1.362E-02
Vm-15	15	9.700E-01	9.703E-01	PF 98-100	158	-5.257E-02	-5.166E-02
Vm-17	17	9.951E-01	1.000E+00	PF 99-100	159	-2.265E-01	-2.226E-01

Vm-18	18	9.730E-01	9.768E-01	PF 100-101	160	-1.674E-01	-1.698E-01
Vm-21	21	9.577E-01	9.604E-01	PF 101-102	162	-3.898E-01	-3.877E-01
Vm-23	23	9.995E-01	1.000E+00	PF 100-106	167	6.036E-01	5.930E-01
Vm-24	24	9.920E-01	9.873E-01	PF 105-108	171	2.397E-01	2.396E-01
Vm-25	25	1.050E+00	1.054E+00	PF 108-109	173	2.177E-01	2.154E-01
Vm-27	27	9.680E-01	9.732E-01	PF 109-110	175	1.371E-01	1.389E-01
Vm-28	28	9.616E-01	9.598E-01	PF 17-113	178	2.056E-02	2.065E-02
Vm-29	29	9.632E-01	9.696E-01	PF 27-115	181	2.072E-01	2.104E-01
Vm-30	30	9.853E-01	9.891E-01	PF 114-115	182	1.358E-02	1.378E-02
Vm-34	34	9.840E-01	9.922E-01	PF 12-117	184	2.015E-01	2.001E-01
Vm-36	36	9.800E-01	9.866E-01	PF 75-118	185	4.021E-01	3.946E-01
Vm-37	37	9.907E-01	9.967E-01	PF 76-118	186	-6.850E-02	-6.763E-02
Vm-40	40	9.700E-01	9.747E-01	PT 11-12	12	-3.415E-01	-3.444E-01
Vm-42	42	9.850E-01	9.796E-01	PT 11-13	16	-3.477E-01	-3.450E-01
Vm-44	44	9.844E-01	9.748E-01	PT 13-15	18	-7.670E-03	-7.751E-03
Vm-45	45	9.864E-01	9.905E-01	PT 15-17	21	1.054E+00	1.068E+00
Vm-46	46	1.005E+00	1.005E+00	PT 18-19	24	-1.931E-01	-1.964E-01
Vm-49	49	1.025E+00	1.033E+00	PT 20-21	27	2.884E-01	2.920E-01
Vm-51	51	9.669E-01	9.762E-01	PT 21-22	28	4.326E-01	4.249E-01
Vm-53	53	9.460E-01	9.407E-01	PT 22-23	29	5.430E-01	5.341E-01
Vm-54	54	9.550E-01	9.515E-01	PT 23-25	31	1.668E+00	1.696E+00
Vm-56	56	9.540E-01	9.511E-01	PT 26-25	32	-9.029E-01	-9.028E-01
Vm-57	57	9.706E-01	9.646E-01	PT 27-28	34	-3.266E-01	-3.295E-01
Vm-59	59	9.850E-01	9.915E-01	PT 8-30	37	-7.381E-01	-7.443E-01
Vm-62	62	9.980E-01	9.923E-01	PT 29-31	40	8.432E-02	8.478E-02
Vm-63	63	9.687E-01	9.648E-01	PT 19-34	45	3.647E-02	3.604E-02
Vm-64	64	9.837E-01	9.782E-01	PT 35-37	47	3.399E-01	3.413E-01
Vm-68	68	1.003E+00	9.981E-01	PT 33-37	48	1.586E-01	1.581E-01
Vm-69	69	1.035E+00	1.043E+00	PT 30-38	54	-6.209E-01	-6.122E-01
Vm-70	70	9.840E-01	9.887E-01	PT 40-42	57	1.193E-01	1.197E-01
Vm-71	71	9.868E-01	9.886E-01	PT 41-42	58	2.181E-01	2.177E-01
Vm-73	73	9.910E-01	9.973E-01	PT 46-47	63	3.148E-01	3.201E-01
Vm-75	75	9.673E-01	9.578E-01	PT 42-49	66	6.804E-01	6.887E-01
Vm-76	76	9.430E-01	9.415E-01	PT 42-49	67	6.804E-01	6.755E-01
Vm-77	77	1.006E+00	1.012E+00	PT 48-49	69	3.511E-01	3.514E-01
Vm-80	80	1.040E+00	1.049E+00	PT 49-50	70	-5.288E-01	-5.205E-01
Vm-82	82	9.885E-01	9.897E-01	PT 49-51	71	-6.435E-01	-6.555E-01
Vm-85	85	9.850E-01	9.763E-01	PT 51-52	72	-2.837E-01	-2.866E-01
Vm-86	86	9.867E-01	9.875E-01	PT 49-54	75	-3.658E-01	-3.600E-01
Vm-91	91	9.800E-01	9.868E-01	PT 54-56	78	-1.852E-01	-1.863E-01
Vm-92	92	9.900E-01	9.806E-01	PT 55-56	79	2.145E-01	2.185E-01
Vm-94	94	9.898E-01	9.921E-01	PT 56-58	82	6.686E-02	6.612E-02

Vm-100	100	1.017E+00	1.022E+00	PT 54-59	84	3.090E-01	3.031E-01
Vm-101	101	9.914E-01	9.859E-01	PT 56-59	86	3.007E-01	3.039E-01
Vm-102	102	9.891E-01	9.915E-01	PT 59-61	89	5.264E-01	5.182E-01
Vm-103	103	1.010E+00	1.014E+00	PT 60-61	90	1.124E+00	1.102E+00
Vm-105	105	9.650E-01	9.742E-01	PT 63-59	93	-1.518E+00	-1.504E+00
Vm-107	107	9.520E-01	9.527E-01	PT 63-64	94	1.523E+00	1.540E+00
Vm-110	110	9.730E-01	9.825E-01	PT 49-66	98	1.352E+00	1.347E+00
Vm-111	111	9.800E-01	9.782E-01	PT 62-66	100	3.793E-01	3.833E-01
Vm-112	112	9.750E-01	9.667E-01	PT 65-66	102	-8.541E-02	-8.711E-02
Vm-113	113	9.930E-01	9.858E-01	PT 66-67	103	-5.250E-01	-5.210E-01
Vm-114	114	9.601E-01	9.645E-01	PT 49-69	106	4.878E-01	4.913E-01
PG-3	3	-3.900E-01	-3.849E-01	PT 68-69	107	1.258E+00	1.243E+00
PG-4	4	-3.900E-01	-3.958E-01	PT 24-70	109	6.216E-02	6.172E-02
PG-8	8	-2.800E-01	-2.824E-01	PT 24-72	111	-1.450E-02	-1.479E-02
PG-9	9	0.000E+00	0.000E+00	PT 70-74	114	-1.601E-01	-1.601E-01
PG-12	12	3.800E-01	3.848E-01	PT 69-77	119	-6.105E-01	-6.042E-01
PG-13	13	-3.400E-01	-3.381E-01	PT 75-77	120	3.541E-01	3.483E-01
PG-15	15	-9.000E-01	-8.950E-01	PT 79-80	125	6.550E-01	6.666E-01
PG-16	16	-2.500E-01	-2.480E-01	PT 82-83	129	4.756E-01	4.827E-01
PG-19	19	-4.500E-01	-4.509E-01	PT 85-86	133	-1.705E-01	-1.726E-01
PG-20	20	-1.800E-01	-1.776E-01	PT 86-87	134	4.000E-02	3.985E-02
PG-24	24	-1.300E-01	-1.323E-01	PT 88-89	137	1.003E+00	1.007E+00
PG-25	25	2.200E+00	2.243E+00	PT 89-90	139	-1.079E+00	-1.088E+00
PG-30	30	0.000E+00	0.000E+00	PT 92-94	145	-5.075E-01	-5.024E-01
PG-31	31	-3.600E-01	-3.664E-01	PT 94-96	150	-1.966E-01	-1.949E-01
PG-33	33	-2.300E-01	-2.314E-01	PT 80-98	152	-2.874E-01	-2.837E-01
PG-35	35	-3.300E-01	-3.295E-01	PT 94-100	155	-3.866E-02	-3.901E-02
PG-36	36	-3.100E-01	-3.044E-01	PT 96-97	157	1.118E-01	1.119E-01
PG-38	38	0.000E+00	0.000E+00	PT 100-103	163	-1.194E+00	-1.190E+00
PG-42	42	-9.600E-01	-9.690E-01	PT 104-105	168	-4.833E-01	-4.854E-01
PG-44	44	-1.600E-01	-1.581E-01	PT 105-105	169	-8.848E-02	-8.751E-02
PG-46	46	-9.000E-02	-8.840E-02	PT 106-107	172	-2.365E-01	-2.379E-01
PG-47	47	-3.400E-01	-3.455E-01	PT 108-109	173	-2.171E-01	-2.143E-01
PG-49	49	1.170E+00	1.164E+00	PT 32-113	179	-3.948E-02	-3.903E-02
PG-52	52	-1.800E-01	-1.806E-01	PT 32-114	180	-9.358E-02	-9.344E-02
PG-53	53	-2.300E-01	-2.321E-01	PT 68-116	183	-1.840E+00	-1.826E+00
PG-54	54	-6.500E-01	-6.479E-01	QF 1-2	1	-1.304E-01	-1.267E-01
PG-55	55	-6.300E-01	-6.404E-01	QF 3-5	4	-1.449E-01	-1.483E-01
PG-61	61	1.600E+00	1.591E+00	QF 5-6	5	4.106E-02	4.148E-02
PG-63	63	0.000E+00	0.000E+00	QF 6-7	6	-4.772E-02	-4.931E-02
PG-64	64	0.000E+00	0.000E+00	QF 9-10	9	-2.443E-01	-2.443E-01
PG-66	66	3.530E+00	3.567E+00	QF 4-11	10	-2.177E-03	-2.142E-03
PG-68	68	0.000E+00	0.000E+00	QF 5-11	11	2.966E-02	2.896E-02

PG-70	70	-6.600E-01	-6.498E-01	QF 2-12	13	-2.001E-01	-2.066E-01
PG-71	71	0.000E+00	0.000E+00	QF 7-12	15	-6.505E-02	-6.643E-02
PG-77	77	-6.100E-01	-6.014E-01	QF 12-14	17	2.623E-02	2.609E-02
PG-79	79	-3.900E-01	-3.952E-01	QF 14-15	19	3.141E-02	3.229E-02
PG-81	81	0.000E+00	0.000E+00	QF 17-18	23	2.476E-01	2.400E-01
PG-83	83	-2.000E-01	-2.017E-01	QF 21-22	28	-2.099E-02	-2.143E-02
PG-85	85	-2.400E-01	-2.384E-01	QF 23-24	30	1.042E-01	1.059E-01
PG-86	86	-2.100E-01	-2.101E-01	QF 28-29	35	-6.568E-02	-6.392E-02
PG-90	90	-1.630E+00	-1.641E+00	QF 30-17	36	9.297E-01	9.583E-01
PG-92	92	-6.500E-01	-6.440E-01	QF 17-31	39	1.152E-01	1.136E-01
PG-96	96	-3.800E-01	-3.754E-01	QF 23-32	41	5.054E-02	4.962E-02
PG-97	97	-1.500E-01	-1.484E-01	QF 34-36	49	4.695E-02	4.859E-02
PG-98	98	-3.400E-01	-3.426E-01	QF 37-40	53	-3.675E-02	-3.799E-02
PG-99	99	-4.200E-01	-4.243E-01	QF 39-40	55	-8.702E-02	-8.994E-02
PG-102	102	-5.000E-02	-4.914E-02	QF 40-41	56	1.193E-02	1.162E-02
PG-104	104	-3.800E-01	-3.732E-01	QF 43-44	59	-1.330E-02	-1.357E-02
PG-105	105	-3.100E-01	-3.093E-01	QF 34-43	60	1.633E-02	1.688E-02
PG-110	110	-3.900E-01	-3.969E-01	QF 46-48	64	-5.831E-02	-5.609E-02
PG-111	111	3.600E-01	3.566E-01	QF 45-49	68	-2.083E-02	-2.085E-02
PG-112	112	-6.800E-01	-6.720E-01	QF 52-53	73	1.994E-02	1.979E-02
PG-116	116	-1.840E+00	-1.868E+00	QF 54-55	77	1.457E-02	1.468E-02
PG-117	117	-2.000E-01	-1.997E-01	QF 56-57	80	-9.104E-02	-9.377E-02
PG-118	118	-3.300E-01	-3.321E-01	QF 50-57	81	9.141E-02	8.784E-02
QG-3	3	-1.000E-01	-1.028E-01	QF 51-58	83	3.159E-02	3.133E-02
QG-4	4	-2.701E-01	-2.755E-01	QF 59-60	88	3.574E-02	3.636E-02
QG-8	8	6.314E-01	6.283E-01	QF 60-62	91	-7.114E-02	-7.360E-02
QG-9	9	0.000E+00	0.000E+00	QF 64-65	97	-6.649E-01	-6.705E-01
QG-12	12	8.129E-01	8.385E-01	QF 62-67	101	-1.441E-01	-1.480E-01
QG-13	13	-1.600E-01	-1.639E-01	QF 65-68	104	-2.243E-01	-2.251E-01
QG-15	15	-2.284E-01	-2.335E-01	QF 47-69	105	1.163E-01	1.167E-01
QG-16	16	-1.000E-01	-1.035E-01	QF 71-72	112	-9.397E-03	-9.354E-03
QG-19	19	-3.927E-01	-4.078E-01	QF 71-73	113	-1.074E-01	-1.068E-01
QG-20	20	-3.000E-02	-3.007E-02	QF 69-75	116	2.049E-01	2.124E-01
QG-24	24	-1.491E-01	-1.525E-01	QF 74-75	117	-6.190E-02	-6.044E-02
QG-25	25	5.004E-01	5.166E-01	QF 76-77	118	-2.104E-01	-2.104E-01
QG-30	30	0.000E+00	0.000E+00	QF 78-79	122	-1.837E-01	-1.824E-01
QG-31	31	5.586E-02	5.790E-02	QF 81-80	127	7.554E-01	7.379E-01
QG-33	33	-9.000E-02	-8.828E-02	QF 77-82	128	1.755E-01	1.758E-01
QG-35	35	-9.000E-02	-9.095E-02	QF 84-85	132	8.992E-02	8.952E-02
QG-36	36	-9.275E-02	-9.591E-02	QF 86-87	134	-1.509E-01	-1.557E-01
QG-37	37	0.000E+00	0.000E+00	QF 85-88	135	7.600E-02	7.311E-02
QG-38	38	0.000E+00	0.000E+00	QF 91-92	143	-6.626E-02	-6.628E-02
QG-42	42	1.803E-01	1.818E-01	QF 92-93	144	-1.166E-01	-1.143E-01
QG-44	44	-8.000E-02	-7.803E-02	QF 94-95	147	9.014E-02	9.336E-02
QG-46	46	-1.503E-01	-1.522E-01	QF 82-96	149	-6.569E-02	-6.484E-02
QG-47	47	0.000E+00	0.000E+00	QF 92-100	154	-1.653E-01	-1.713E-01
QG-49	49	8.585E-01	8.283E-01	QF 95-96	156	-2.169E-01	-2.188E-01

QG-52	52	-5.000E-02	-4.866E-02	QF 98-100	158	2.429E-02	2.380E-02
QG-53	53	-1.100E-01	-1.082E-01	QF 99-100	159	-4.594E-02	-4.669E-02
QG-54	54	-2.810E-01	-2.778E-01	QF 100-101	160	2.290E-01	2.323E-01
QG-55	55	-1.734E-01	-1.737E-01	QF 101-102	162	1.013E-01	1.027E-01
QG-61	61	-4.039E-01	-3.930E-01	QF 100-106	167	9.476E-02	9.133E-02
QG-63	63	0.000E+00	0.000E+00	QF 105-108	171	-1.113E-01	-1.074E-01
QG-64	64	0.000E+00	0.000E+00	QF 108-109	173	-1.092E-01	-1.134E-01
QG-66	66	-1.996E-01	-2.026E-01	QF 109-110	175	-1.339E-01	-1.392E-01
QG-68	68	0.000E+00	0.000E+00	QF 17-113	178	5.901E-02	5.665E-02
QG-70	70	-1.033E-01	-1.048E-01	QF 27-115	181	5.060E-02	5.157E-02
QG-71	71	0.000E+00	0.000E+00	QF 114-115	182	2.207E-03	2.150E-03
QG-77	77	-1.583E-01	-1.630E-01	QF 12-117	184	5.197E-02	5.292E-02
QG-79	79	-3.200E-01	-3.166E-01	QF 75-118	185	2.359E-01	2.421E-01
QG-81	81	0.000E+00	0.000E+00	QF 76-118	186	-9.692E-02	-9.950E-02
QG-83	83	-1.000E-01	-9.721E-02	QT 11-12	12	3.513E-01	3.379E-01
QG-85	85	-2.061E-01	-2.070E-01	QT 11-13	16	-1.216E-01	-1.259E-01
QG-86	86	-1.000E-01	-9.893E-02	QT 13-15	18	-2.040E-02	-2.017E-02
QG-89	89	-5.905E-02	-5.843E-02	QT 15-17	21	2.522E-01	2.547E-01
QG-90	90	1.731E-01	1.751E-01	QT 18-19	24	-1.755E-01	-1.723E-01
QG-92	92	-2.396E-01	-2.305E-01	QT 20-21	27	-5.901E-02	-5.782E-02
QG-96	96	-1.500E-01	-1.482E-01	QT 21-22	28	1.758E-02	1.795E-02
QG-97	97	-9.000E-02	-9.311E-02	QT 22-23	29	7.686E-02	7.489E-02
QG-98	98	-8.000E-02	-8.251E-02	QT 23-25	31	3.863E-01	3.793E-01
QG-99	99	-1.754E-01	-1.684E-01	QT 26-25	32	-1.864E-01	-1.919E-01
QG-102	102	-3.000E-02	-2.978E-02	QT 27-28	34	-4.321E-03	-4.424E-03
QG-104	104	-2.261E-01	-2.255E-01	QT 8-30	37	-7.542E-01	-7.834E-01
QG-105	105	-4.433E-01	-4.472E-01	QT 29-31	40	7.920E-02	8.027E-02
QG-110	110	-2.972E-01	-2.865E-01	QT 19-34	45	4.597E-02	4.521E-02
QG-111	111	-1.844E-02	-1.864E-02	QT 35-37	47	1.243E-01	1.219E-01
QG-112	112	2.851E-01	2.812E-01	QT 33-37	48	7.459E-02	7.676E-02
QG-116	116	5.132E-01	4.975E-01	QT 30-38	54	-5.598E-01	-5.403E-01
QG-117	117	-8.000E-02	-7.999E-02	QT 40-42	57	2.302E-02	2.213E-02
QG-118	118	-1.500E-01	-1.544E-01	QT 41-42	58	5.238E-02	5.270E-02
PF 1-2	1	-1.235E-01	-1.248E-01	QT 46-47	63	-7.948E-03	-8.030E-03
PF 3-5	4	-6.811E-01	-6.751E-01	QT 42-49	66	3.702E-03	3.698E-03
PF 5-6	5	8.847E-01	8.771E-01	QT 42-49	67	3.702E-03	3.771E-03

PF 6-7	6	3.554E-01	3.614E-01	QT 48-49	69	-3.925E-02	-3.879E-02
PF 9-10	9	-4.453E+00	-4.437E+00	QT 49-50	70	-1.314E-01	-1.303E-01
PF 4-11	10	6.423E-01	6.419E-01	QT 49-51	71	-1.740E-01	-1.775E-01
PF 5-11	11	7.722E-01	7.812E-01	QT 51-52	72	-6.994E-02	-7.214E-02
PF 2-12	13	-3.245E-01	-3.309E-01	QT 49-54	75	-1.560E-01	-1.577E-01
PF 7-12	15	1.648E-01	1.617E-01	QT 54-56	78	-4.975E-02	-4.956E-02
PF 12-14	17	1.831E-01	1.837E-01	QT 55-56	79	5.566E-02	5.377E-02
PF 14-15	19	4.238E-02	4.222E-02	QT 56-58	82	1.533E-02	1.532E-02
PF 17-18	23	8.027E-01	8.065E-01	QT 54-59	84	4.257E-02	4.317E-02
PF 21-22	28	-4.284E-01	-4.366E-01	QT 56-59	86	1.130E-02	1.130E-02
PF 23-24	30	8.284E-02	8.281E-02	QT 59-61	89	-4.626E-02	-4.759E-02
PF 28-29	35	1.566E-01	1.557E-01	QT 60-61	90	-8.227E-02	-8.314E-02
PF 30-17	36	2.312E+00	2.271E+00	QT 63-59	93	-5.702E-01	-5.856E-01
PF 17-31	39	1.477E-01	1.473E-01	QT 63-64	94	5.251E-01	5.083E-01
PF 23-32	41	9.298E-01	9.357E-01	QT 49-66	98	8.325E-02	8.530E-02
PF 34-36	49	3.025E-01	2.981E-01	QT 62-66	100	1.468E-01	1.514E-01
PF 37-40	53	4.402E-01	4.325E-01	QT 65-66	102	-7.055E-01	-6.965E-01
PF 39-40	55	2.692E-01	2.706E-01	QT 66-67	103	-1.915E-01	-1.917E-01
PF 40-41	56	1.545E-01	1.569E-01	QT 49-69	106	-1.206E-01	-1.240E-01
PF 43-44	59	-1.659E-01	-1.655E-01	QT 68-69	107	-1.036E+00	-1.004E+00
PF 34-43	60	1.414E-02	1.398E-02	QT 24-70	109	-6.802E-02	-7.014E-02
PF 46-48	64	-1.476E-01	-1.475E-01	QT 24-72	111	-7.982E-02	-7.758E-02
PF 45-49	68	-4.970E-01	-4.872E-01	QT 70-74	114	-1.542E-01	-1.599E-01
PF 52-53	73	1.037E-01	1.033E-01	QT 69-77	119	-1.380E-01	-1.372E-01
PF 54-55	77	7.073E-02	7.136E-02	QT 75-77	120	7.376E-02	7.597E-02
PF 56-57	80	-2.299E-01	-2.260E-01	QT 79-80	125	3.108E-01	2.989E-01
PF 50-57	81	3.588E-01	3.629E-01	QT 82-83	129	-2.699E-01	-2.697E-01
PF 51-58	83	1.879E-01	1.886E-01	QT 85-86	133	5.091E-02	4.972E-02
PF 59-60	88	-4.332E-01	-4.372E-01	QT 86-87	134	1.102E-01	1.112E-01
PF 60-62	91	-9.872E-02	-1.004E-01	QT 88-89	137	7.699E-02	7.560E-02
PF 64-65	97	-1.828E+00	-1.860E+00	QT 89-90	139	7.071E-02	7.247E-02
PF 62-67	101	-2.430E-01	-2.387E-01	QT 92-94	145	1.591E-01	1.633E-01
PF 65-68	104	1.418E-01	1.442E-01	QT 94-96	150	7.977E-02	7.991E-02
PF 47-69	105	-5.594E-01	-5.525E-01	QT 80-98	152	-1.043E-01	-1.038E-01
PF 71-72	112	1.060E-01	1.072E-01	QT 94-100	155	4.581E-01	4.462E-01
PF 71-73	113	6.012E-02	5.925E-02	QT 96-97	157	1.819E-01	1.884E-01
PF 69-75	116	1.100E+00	1.102E+00	QT 100-103	163	2.436E-01	2.370E-01
PF 74-75	117	-5.199E-01	-5.134E-01	QT 104-105	168	-2.606E-02	-2.595E-02
PF 76-77	118	-6.115E-01	-6.192E-01	QT 105-105	169	-5.152E-02	-5.060E-02
PF 78-79	122	-2.568E-01	-2.595E-01	QT 106-107	172	5.505E-03	5.305E-03
PF 81-80	127	-4.420E-01	-4.435E-01	QT 108-109	173	1.039E-01	1.055E-01
PF 77-82	128	-3.025E-02	-3.035E-02	QT 32-113	179	1.340E-01	1.336E-01

PF 84-85	132	-3.635E-01	-3.682E-01	QT 32-114	180	-3.221E-02	-3.219E-02
PF 86-87	134	-3.947E-02	-3.923E-02	QT 68-116	183	5.132E-01	4.934E-01
PF 85-88	135	-5.039E-01	-4.945E-01				

APPENDIX B

DETAILED STATE ESTIMATION RESULTS

The detailed SE results are prepared in MS Excel sheets for IEEE 14, IEEE 30 and IEEE 118 bus system. There are around 150 MS Excel sheets for results, so it is difficult to provide all sheets in appendix. The results of IEEE 30 bus system with PMU-3 are presented in the appendix. The remaining MS Excel sheets will be provided into CD for future reference.

B.1. IEEE 14 Bus System

B.1.1. White Noise

The results are available in attached CD.

B.1.2. Single Bad-Data as Power Flow Meter

The results are available in attached CD.

B.1.3. Single Bad-Data as Power Injection Meter

The results are available in attached CD.

B.1.4. Single Bad-Data as Voltage Magnitude Meter

The results are available in attached CD.

B.1.5. Multiple Non-Interacting Bad-Data

The results are available in attached CD.

B.1.6. Multiple Interacting Bad-Data

The results are available in attached CD.

B.2. IEEE 30 Bus System

B.2.1. White Noise

Table B.1 IEEE 30 Bus System – White Noise Only

IEEE 30 bus system - White Noise Only						
Sr	Type	Actual	Measurement	Estimated		
				WLS	WLAV	LMR
1	Vm-1	1.0600	1.0600	1.0600	1.0600	1.0607
2	Vm-2	1.0450	NA	1.0450	1.0450	1.0457
3	Vm-3	1.0212	1.0212	1.0212	1.0212	1.0217
4	Vm-4	1.0123	1.0133	1.0123	1.0123	1.0128
5	Vm-5	1.0100	1.0176	1.0103	1.0102	1.0107
6	Vm-6	1.0106	NA	1.0105	1.0106	1.0111
7	Vm-7	1.0026	NA	1.0025	1.0027	1.0031
8	Vm-8	1.0100	1.0010	1.0097	1.0101	1.0106
9	Vm-9	1.0511	NA	1.0526	1.0523	1.0514
10	Vm-10	1.0454	1.0491	1.0476	1.0477	1.0458
11	Vm-11	1.0820	NA	1.0832	1.0823	1.0818
12	Vm-12	1.0573	1.0557	1.0577	1.0570	1.0572
13	Vm-13	1.0710	NA	1.0713	1.0705	1.0707
14	Vm-14	1.0425	NA	1.0433	1.0428	1.0425
15	Vm-15	1.0379	NA	1.0389	1.0388	1.0380
16	Vm-16	1.0446	NA	1.0458	1.0456	1.0447
17	Vm-17	1.0402	NA	1.0424	1.0424	1.0404
18	Vm-18	1.0284	1.0294	1.0298	1.0294	1.0286
19	Vm-19	1.0259	NA	1.0275	1.0270	1.0261
20	Vm-20	1.0300	NA	1.0317	1.0311	1.0302
21	Vm-21	1.0330	1.0431	1.0357	1.0362	1.0334
22	Vm-22	1.0335	NA	1.0363	1.0370	1.0340
23	Vm-23	1.0274	NA	1.0291	1.0307	1.0276
24	Vm-24	1.0218	1.0252	1.0235	1.0252	1.0222
25	Vm-25	1.0176	1.0098	1.0153	1.0098	1.0178

26	Vm-26	0.9999	1.0022	1.0009	1.0022	1.0005
27	Vm-27	1.0235	NA	1.0219	1.0228	1.0237
28	Vm-28	1.0071	1.0052	1.0059	1.0052	1.0075
29	Vm-29	1.0037	1.0042	1.0039	1.0042	1.0037
30	Vm-30	0.9922	NA	0.9917	0.9922	0.9921
31	PG-1	2.6096	2.6103	2.6094	2.6096	2.6115
32	PG-2	0.1830	0.1822	0.1830	0.1817	0.1806
33	PG-3	-0.0240	NA	-0.0240	-0.0240	-0.0245
34	PG-4	-0.0760	-0.0751	-0.0716	-0.0751	-0.0747
35	PG-5	-0.9420	-0.9366	-0.9377	-0.9366	-0.9370
36	PG-6	0.0000	NA	-0.0099	-0.0086	-0.0047
37	PG-7	-0.2280	-0.2306	-0.2326	-0.2306	-0.2311
38	PG-8	-0.3000	NA	-0.2969	-0.2959	-0.2969
39	PG-9	0.0000	NA	0.0000	0.0000	0.0006
40	PG-10	-0.0580	-0.0571	-0.0569	-0.0571	-0.0576
41	PG-11	0.0000	NA	0.0000	0.0000	0.0000
42	PG-12	-0.1120	NA	-0.1199	-0.1108	-0.1176
43	PG-13	0.0000	NA	0.0000	0.0000	0.0000
44	PG-14	-0.0620	-0.0613	-0.0620	-0.0613	-0.0619
45	PG-15	-0.0820	-0.0813	-0.0807	-0.0813	-0.0808
46	PG-16	-0.0350	-0.0349	-0.0358	-0.0349	-0.0354
47	PG-17	-0.0900	NA	-0.0879	-0.0906	-0.0896
48	PG-18	-0.0320	-0.0322	-0.0317	-0.0322	-0.0317
49	PG-19	-0.0950	-0.0944	-0.0949	-0.0944	-0.0949
50	PG-20	-0.0220	NA	-0.0221	-0.0232	-0.0220
51	PG-21	-0.1750	-0.1780	-0.1767	-0.1777	-0.1772
52	PG-22	0.0000	NA	0.0031	-0.0005	0.0004
53	PG-23	-0.0320	NA	-0.0315	-0.0329	-0.0328
54	PG-24	-0.0870	-0.0856	-0.0848	-0.0856	-0.0860
55	PG-25	0.0000	NA	-0.0043	-0.0014	-0.0009
56	PG-26	-0.0350	NA	-0.0340	-0.0354	-0.0347
57	PG-27	0.0000	NA	-0.0004	0.0013	-0.0027
58	PG-28	0.0000	NA	0.0063	0.0025	0.0073
59	PG-29	-0.0240	-0.0236	-0.0239	-0.0236	-0.0241
60	PG-30	-0.1060	-0.1057	-0.1062	-0.1057	-0.1062
61	QG-1	-0.2042	-0.2064	-0.2049	-0.2042	-0.2045
62	QG-2	0.4337	0.4435	0.4345	0.4326	0.4366
63	QG-3	-0.0120	NA	-0.0120	-0.0120	-0.0110
64	QG-4	-0.0160	-0.0154	-0.0143	-0.0150	-0.0148
65	QG-5	0.1666	0.1659	0.1690	0.1670	0.1661
66	QG-6	0.0000	NA	0.0052	0.0212	0.0020
67	QG-7	-0.1090	-0.1109	-0.1089	-0.1087	-0.1103
68	QG-8	0.0611	NA	0.0609	0.0727	0.0631
69	QG-9	0.0000	NA	0.0033	0.0000	0.0006
70	QG-10	-0.0200	-0.0207	-0.0192	-0.0207	-0.0201
71	QG-11	0.1606	NA	0.1594	0.1559	0.1580
72	QG-12	-0.0750	NA	-0.0796	-0.0957	-0.0778
73	QG-13	0.1045	NA	0.1036	0.1036	0.1031
74	QG-14	-0.0160	-0.0163	-0.0153	-0.0163	-0.0158
75	QG-15	-0.0250	-0.0255	-0.0259	-0.0255	-0.0250
76	QG-16	-0.0180	-0.0180	-0.0199	-0.0180	-0.0185
77	QG-17	-0.0580	NA	-0.0528	-0.0513	-0.0581

78	QG-18	-0.0090	-0.0087	-0.0087	-0.0087	-0.0083
79	QG-19	-0.0340	-0.0348	-0.0342	-0.0348	-0.0343
80	QG-20	-0.0070	NA	-0.0076	-0.0116	-0.0075
81	QG-21	-0.1120	-0.1106	-0.1076	-0.1106	-0.1101
82	QG-22	0.0000	NA	0.0116	0.0209	0.0009
83	QG-23	-0.0160	NA	-0.0130	-0.0036	-0.0160
84	QG-24	-0.0670	-0.0666	-0.0621	-0.0342	-0.0670
85	QG-25	0.0000	NA	-0.0221	-0.0944	-0.0004
86	QG-26	-0.0230	NA	-0.0149	0.0040	-0.0222
87	QG-27	0.0000	NA	-0.0041	0.0332	-0.0005
88	QG-28	0.0000	NA	-0.0226	-0.0460	-0.0025
89	QG-29	-0.0090	NA	-0.0030	-0.0050	-0.0090
90	QG-30	-0.0190	-0.0190	-0.0185	-0.0190	-0.0195
91	PF 1-2	1.7331	NA	1.7329	1.7331	1.7342
92	PF 1-3	0.8765	0.8707	0.8765	0.8765	0.8772
93	PF 2-4	0.4365	0.4395	0.4366	0.4365	0.4370
94	PF 3-4	0.8214	NA	0.8214	0.8214	0.8217
95	PF 2-5	0.8236	0.8199	0.8228	0.8216	0.8217
96	PF 2-6	0.6038	NA	0.6044	0.6045	0.6040
97	PF 4-6	0.7213	0.7291	0.7236	0.7242	0.7203
98	PF 5-7	-0.1478	-0.1474	-0.1443	-0.1442	-0.1446
99	PF 6-7	0.3813	0.3870	0.3824	0.3803	0.3811
100	PF 6-8	0.2956	0.2917	0.2919	0.2917	0.2921
101	PF 6-9	0.2772	0.2717	0.2779	0.2796	0.2786
102	PF 6-10	0.1584	0.1596	0.1588	0.1598	0.1593
103	PF 9-11	0.0000	NA	0.0000	0.0000	0.0000
104	PF 9-10	0.2772	NA	0.2779	0.2796	0.2792
105	PF 4-12	0.4419	NA	0.4441	0.4400	0.4449
106	PF 12-13	0.0000	NA	0.0000	0.0000	0.0000
107	PF 12-14	0.0786	0.0800	0.0777	0.0777	0.0781
108	PF 12-15	0.1789	NA	0.1759	0.1788	0.1775
109	PF 12-16	0.0724	0.0727	0.0706	0.0727	0.0716
110	PF 14-15	0.0158	0.0156	0.0150	0.0156	0.0155
111	PF 16-17	0.0369	NA	0.0342	0.0373	0.0357
112	PF 15-18	0.0602	0.0593	0.0589	0.0601	0.0594
113	PF 18-19	0.0278	0.0281	0.0268	0.0276	0.0274
114	PF 19-20	-0.0673	NA	-0.0681	-0.0669	-0.0675
115	PF 10-20	0.0903	NA	0.0912	0.0911	0.0905
116	PF 10-17	0.0533	0.0536	0.0538	0.0536	0.0541
117	PF 10-21	0.1579	NA	0.1585	0.1604	0.1594
118	PF 10-22	0.0762	NA	0.0763	0.0773	0.0768
119	PF 21-22	-0.0183	NA	-0.0193	-0.0184	-0.0189
120	PF 15-23	0.0504	NA	0.0492	0.0508	0.0505
121	PF 22-24	0.0574	0.0580	0.0595	0.0580	0.0578
122	PF 23-24	0.0180	0.0179	0.0174	0.0177	0.0174
123	PF 24-25	-0.0121	-0.0118	-0.0085	-0.0104	-0.0113
124	PF 25-26	0.0354	0.0357	0.0344	0.0357	0.0352
125	PF 25-27	-0.0476	-0.0480	-0.0473	-0.0480	-0.0475
126	PF 28-27	0.1807	0.1793	0.1809	0.1793	0.1836
127	PF 27-29	0.0619	NA	0.0619	0.0615	0.0621
128	PF 27-30	0.0709	0.0722	0.0710	0.0706	0.0711
129	PF 29-30	0.0370	0.0371	0.0372	0.0371	0.0371

130	PF 8-28	-0.0054	NA	-0.0061	-0.0053	-0.0059
131	PF 6-28	0.1867	NA	0.1813	0.1828	0.1828
132	PT 2-1	-1.6809	-1.6536	-1.6808	-1.6809	-1.6821
133	PT 3-1	-0.8454	NA	-0.8454	-0.8454	-0.8461
134	PT 4-2	-0.4263	NA	-0.4264	-0.4263	-0.4268
135	PT 4-3	-0.8129	-0.8014	-0.8129	-0.8129	-0.8131
136	PT 5-2	-0.7942	NA	-0.7934	-0.7923	-0.7925
137	PT 6-2	-0.5843	-0.5796	-0.5849	-0.5850	-0.5846
138	PT 6-4	-0.7150	NA	-0.7172	-0.7178	-0.7140
139	PT 7-5	0.1495	NA	0.1460	0.1459	0.1462
140	PT 7-6	-0.3775	NA	-0.3785	-0.3765	-0.3773
141	PT 8-6	-0.2946	NA	-0.2909	-0.2906	-0.2911
142	PT 9-6	-0.2772	NA	-0.2779	-0.2796	-0.2786
143	PT 10-6	-0.1584	NA	-0.1588	-0.1598	-0.1593
144	PT 11-9	0.0000	NA	0.0000	0.0000	0.0000
145	PT 10-9	-0.2772	-0.2796	-0.2779	-0.2796	-0.2792
146	PT 12-4	-0.4419	-0.4497	-0.4441	-0.4400	-0.4449
147	PT 13-12	0.0000	NA	0.0000	0.0000	0.0000
148	PT 14-12	-0.0778	NA	-0.0770	-0.0770	-0.0774
149	PT 15-12	-0.1767	-0.1733	-0.1738	-0.1767	-0.1754
150	PT 16-12	-0.0719	NA	-0.0701	-0.0722	-0.0711
151	PT 15-14	-0.0158	NA	-0.0150	-0.0156	-0.0155
152	PT 17-16	-0.0368	NA	-0.0342	-0.0372	-0.0356
153	PT 18-15	-0.0598	NA	-0.0585	-0.0597	-0.0591
154	PT 19-18	-0.0277	NA	-0.0268	-0.0275	-0.0274
155	PT 20-19	0.0674	0.0687	0.0683	0.0670	0.0677
156	PT 20-10	-0.0894	-0.0902	-0.0904	-0.0902	-0.0897
157	PT 17-10	-0.0532	NA	-0.0537	-0.0534	-0.0539
158	PT 21-10	-0.1567	-0.1564	-0.1574	-0.1593	-0.1583
159	PT 22-10	-0.0757	NA	-0.0758	-0.0768	-0.0763
160	PT 22-21	0.0183	0.0184	0.0193	0.0184	0.0189
161	PT 23-15	-0.0500	-0.0507	-0.0489	-0.0506	-0.0502
162	PT 24-22	-0.0569	-0.0568	-0.0590	-0.0575	-0.0573
163	PT 24-23	-0.0180	-0.0177	-0.0174	-0.0177	-0.0174
164	PT 25-24	0.0122	NA	0.0087	0.0110	0.0114
165	PT 26-25	-0.0350	NA	-0.0340	-0.0354	-0.0347
166	PT 27-25	0.0479	NA	0.0476	0.0484	0.0478
167	PT 27-28	-0.1807	-0.1842	-0.1809	-0.1793	-0.1836
168	PT 29-27	-0.0610	NA	-0.0611	-0.0607	-0.0612
169	PT 30-27	-0.0693	NA	-0.0694	-0.0690	-0.0695
170	PT 30-29	-0.0367	-0.0367	-0.0369	-0.0367	-0.0368
171	PT 28-8	0.0055	0.0054	0.0061	0.0054	0.0059
172	PT 28-6	-0.1862	NA	-0.1807	-0.1822	-0.1822
173	QF 1-2	-0.2470	NA	-0.2477	-0.2470	-0.2478
174	QF 1-3	0.0428	0.0421	0.0429	0.0428	0.0433
175	QF 2-4	0.0475	0.0481	0.0477	0.0475	0.0484
176	QF 3-4	-0.0385	NA	-0.0385	-0.0385	-0.0371
177	QF 2-5	0.0278	0.0268	0.0266	0.0268	0.0280
178	QF 2-6	0.0137	NA	0.0148	0.0136	0.0147
179	QF 4-6	-0.1591	-0.1583	-0.1557	-0.1596	-0.1587
180	QF 5-7	0.1149	0.1149	0.1164	0.1149	0.1154
181	QF 6-7	-0.0278	-0.0284	-0.0294	-0.0284	-0.0271

182	QF 6-8	-0.0720	-0.0736	-0.0672	-0.0736	-0.0731
183	QF 6-9	-0.0809	-0.0822	-0.0892	-0.0868	-0.0797
184	QF 6-10	0.0019	NA	-0.0026	-0.0024	0.0022
185	QF 9-11	-0.1560	-0.1516	-0.1549	-0.1516	-0.1535
186	QF 9-10	0.0588	NA	0.0523	0.0480	0.0580
187	QF 4-12	0.1441	NA	0.1426	0.1456	0.1473
188	QF 12-13	-0.1032	-0.1023	-0.1023	-0.1023	-0.1018
189	QF 12-14	0.0240	0.0237	0.0230	0.0215	0.0237
190	QF 12-15	0.0679	NA	0.0647	0.0578	0.0670
191	QF 12-16	0.0335	0.0335	0.0304	0.0262	0.0330
192	QF 14-15	0.0065	0.0063	0.0061	0.0038	0.0064
193	QF 16-17	0.0144	NA	0.0094	0.0071	0.0134
194	QF 15-18	0.0160	0.0153	0.0146	0.0153	0.0155
195	QF 18-19	0.0062	0.0059	0.0051	0.0058	0.0064
196	QF 19-20	-0.0279	NA	-0.0292	-0.0291	-0.0280
197	QF 10-20	0.0371	NA	0.0391	0.0430	0.0376
198	QF 10-17	0.0443	0.0449	0.0440	0.0449	0.0454
199	QF 10-21	0.1001	NA	0.0931	0.0870	0.0985
200	QF 10-22	0.0460	NA	0.0421	0.0376	0.0452
201	QF 21-22	-0.0143	NA	-0.0168	-0.0259	-0.0140
202	QF 15-23	0.0291	NA	0.0263	0.0166	0.0286
203	QF 22-24	0.0306	0.0295	0.0358	0.0315	0.0310
204	QF 23-24	0.0124	0.0125	0.0127	0.0125	0.0120
205	QF 24-25	0.0201	0.0196	0.0306	0.0541	0.0201
206	QF 25-26	0.0237	0.0233	0.0154	-0.0035	0.0228
207	QF 25-27	-0.0037	-0.0038	-0.0072	-0.0376	-0.0033
208	QF 28-27	0.0504	0.0519	0.0514	0.0470	0.0514
209	QF 27-29	0.0167	NA	0.0121	0.0137	0.0169
210	QF 27-30	0.0166	0.0173	0.0146	0.0155	0.0169
211	QF 29-30	0.0061	0.0060	0.0075	0.0072	0.0063
212	QF 8-28	-0.0054	NA	-0.0008	0.0046	-0.0045
213	QF 6-27	0.0011	NA	0.0202	0.0339	0.0036
214	QT 2-1	0.3447	0.3363	0.3453	0.3447	0.3454
215	QT 3-1	0.0265	NA	0.0265	0.0265	0.0261
216	QT 4-2	-0.0554	NA	-0.0556	-0.0554	-0.0564
217	QT 4-3	0.0544	0.0525	0.0544	0.0544	0.0530
218	QT 5-2	0.0517	NA	0.0526	0.0521	0.0507
219	QT 6-2	0.0058	0.0060	0.0049	0.0060	0.0047
220	QT 6-4	0.1719	NA	0.1685	0.1725	0.1714
221	QT 7-5	-0.1313	NA	-0.1329	-0.1314	-0.1319
222	QT 7-6	0.0223	NA	0.0240	0.0228	0.0216
223	QT 8-6	0.0666	NA	0.0617	0.0681	0.0676
224	QT 9-6	0.0972	NA	0.1058	0.1035	0.0961
225	QT 10-6	0.0110	NA	0.0154	0.0155	0.0108
226	QT 11-9	0.1606	NA	0.1594	0.1559	0.1580
227	QT 10-9	-0.0508	-0.0521	-0.0444	-0.0400	-0.0499
228	QT 12-4	-0.0972	-0.1004	-0.0954	-0.0990	-0.0997
229	QT 13-12	0.1045	NA	0.1036	0.1036	0.1031
230	QT 14-12	-0.0225	NA	-0.0215	-0.0201	-0.0222
231	QT 15-12	-0.0636	-0.0629	-0.0606	-0.0537	-0.0628
232	QT 16-12	-0.0324	NA	-0.0293	-0.0251	-0.0319
233	QT 15-14	-0.0064	NA	-0.0061	-0.0037	-0.0063

234	QT 17-16	-0.0141	NA	-0.0092	-0.0068	-0.0131
235	QT 18-15	-0.0152	NA	-0.0138	-0.0146	-0.0147
236	QT 19-18	-0.0061	NA	-0.0050	-0.0057	-0.0063
237	QT 20-19	0.0283	0.0282	0.0296	0.0294	0.0283
238	QT 20-10	-0.0353	-0.0363	-0.0372	-0.0410	-0.0358
239	QT 17-10	-0.0439	NA	-0.0436	-0.0445	-0.0450
240	QT 21-10	-0.0977	-0.0957	-0.0907	-0.0847	-0.0961
241	QT 22-10	-0.0449	NA	-0.0411	-0.0366	-0.0442
242	QT 22-21	0.0143	0.0145	0.0168	0.0260	0.0140
243	QT 23-15	-0.0284	-0.0285	-0.0257	-0.0160	-0.0280
244	QT 24-22	-0.0299	-0.0308	-0.0350	-0.0308	-0.0303
245	QT 24-23	-0.0123	-0.0124	-0.0126	-0.0124	-0.0119
246	QT 25-24	-0.0200	NA	-0.0303	-0.0532	-0.0199
247	QT 26-25	-0.0230	NA	-0.0149	0.0040	-0.0222
248	QT 27-25	0.0042	NA	0.0076	0.0384	0.0038
249	QT 27-28	-0.0375	-0.0379	-0.0385	-0.0344	-0.0381
250	QT 29-27	-0.0151	NA	-0.0105	-0.0122	-0.0152
251	QT 30-27	-0.0136	NA	-0.0116	-0.0125	-0.0139
252	QT 30-29	-0.0054	-0.0054	-0.0069	-0.0066	-0.0056
253	QT 28-8	-0.0380	-0.0395	-0.0426	-0.0479	-0.0390
254	QT 28-6	-0.0123	N/A	-0.0314	-0.0451	-0.0149

B.2.2. Single Bad-Data as Power Flow Meter

Table B.2 IEEE 30 Bus System - Single Bad-Data as Power Flow Meter

IEEE 30 bus system - Single Bad-Data at PF 2-5						
Sr	Type	Actual	Measurement	Estimated		
				WLS	WLAV	LMR
1	Vm-1	1.0600	1.0600	1.0600	1.0600	1.0607
2	Vm-2	1.0450	NA	1.0446	1.0450	1.0457
3	Vm-3	1.0212	1.0212	1.0212	1.0212	1.0217
4	Vm-4	1.0123	1.0133	1.0124	1.0123	1.0128
5	Vm-5	1.0100	1.0176	1.0060	1.0102	1.0107
6	Vm-6	1.0106	NA	1.0113	1.0106	1.0111
7	Vm-7	1.0026	NA	1.0018	1.0027	1.0031
8	Vm-8	1.0100	1.0010	1.0105	1.0101	1.0106
9	Vm-9	1.0511	NA	1.0524	1.0523	1.0514
10	Vm-10	1.0454	1.0491	1.0472	1.0477	1.0457
11	Vm-11	1.0820	NA	1.0827	1.0823	1.0817
12	Vm-12	1.0573	1.0557	1.0592	1.0570	1.0572
13	Vm-13	1.0710	NA	1.0727	1.0705	1.0707
14	Vm-14	1.0425	NA	1.0445	1.0428	1.0425
15	Vm-15	1.0379	NA	1.0399	1.0388	1.0380
16	Vm-16	1.0446	NA	1.0465	1.0456	1.0446
17	Vm-17	1.0402	NA	1.0418	1.0424	1.0404
18	Vm-18	1.0284	1.0294	1.0300	1.0294	1.0286
19	Vm-19	1.0259	NA	1.0273	1.0270	1.0261
20	Vm-20	1.0300	NA	1.0314	1.0311	1.0302
21	Vm-21	1.0330	1.0431	1.0352	1.0362	1.0334

22	Vm-22	1.0335	NA	1.0357	1.0370	1.0339
23	Vm-23	1.0274	NA	1.0295	1.0307	1.0276
24	Vm-24	1.0218	1.0252	1.0233	1.0252	1.0222
25	Vm-25	1.0176	1.0098	1.0151	1.0098	1.0178
26	Vm-26	0.9999	1.0022	1.0009	1.0022	1.0005
27	Vm-27	1.0235	NA	1.0215	1.0228	1.0237
28	Vm-28	1.0071	1.0052	1.0063	1.0052	1.0075
29	Vm-29	1.0037	1.0042	1.0038	1.0042	1.0037
30	Vm-30	0.9922	NA	0.9915	0.9922	0.9921
31	PG-1	2.6096	2.6103	2.6084	2.6096	2.6115
32	PG-2	0.1830	0.1822	-0.0758	0.1817	0.1806
33	PG-3	-0.0240	NA	-0.0241	-0.0240	-0.0245
34	PG-4	-0.0760	-0.0751	-0.1090	-0.0751	-0.0747
35	PG-5	-0.9420	-0.9366	-0.5439	-0.9366	-0.9371
36	PG-6	0.0000	NA	-0.1686	-0.0086	-0.0045
37	PG-7	-0.2280	-0.2306	-0.1513	-0.2306	-0.2311
38	PG-8	-0.3000	NA	-0.2953	-0.2959	-0.2969
39	PG-9	0.0000	NA	0.0000	0.0000	0.0006
40	PG-10	-0.0580	-0.0571	-0.0576	-0.0571	-0.0576
41	PG-11	0.0000	NA	0.0000	0.0000	0.0000
42	PG-12	-0.1120	NA	-0.1571	-0.1108	-0.1176
43	PG-13	0.0000	NA	0.0000	0.0000	0.0000
44	PG-14	-0.0620	-0.0613	-0.0621	-0.0613	-0.0619
45	PG-15	-0.0820	-0.0813	-0.0814	-0.0813	-0.0809
46	PG-16	-0.0350	-0.0349	-0.0398	-0.0349	-0.0354
47	PG-17	-0.0900	NA	-0.0784	-0.0906	-0.0896
48	PG-18	-0.0320	-0.0322	-0.0310	-0.0322	-0.0317
49	PG-19	-0.0950	-0.0944	-0.0942	-0.0944	-0.0949
50	PG-20	-0.0220	NA	-0.0254	-0.0232	-0.0220
51	PG-21	-0.1750	-0.1780	-0.1773	-0.1777	-0.1772
52	PG-22	0.0000	NA	0.0023	-0.0005	0.0003
53	PG-23	-0.0320	NA	-0.0306	-0.0329	-0.0328
54	PG-24	-0.0870	-0.0856	-0.0852	-0.0856	-0.0860
55	PG-25	0.0000	NA	-0.0034	-0.0014	-0.0009
56	PG-26	-0.0350	NA	-0.0340	-0.0354	-0.0347
57	PG-27	0.0000	NA	-0.0001	0.0013	-0.0027
58	PG-28	0.0000	NA	-0.0010	0.0025	0.0072
59	PG-29	-0.0240	-0.0236	-0.0238	-0.0236	-0.0241
60	PG-30	-0.1060	-0.1057	-0.1062	-0.1057	-0.1062
61	QG-1	-0.2042	-0.2064	-0.1982	-0.2042	-0.2045
62	QG-2	0.4337	0.4435	0.4665	0.4326	0.4368
63	QG-3	-0.0120	NA	-0.0129	-0.0120	-0.0111
64	QG-4	-0.0160	-0.0154	-0.0197	-0.0150	-0.0147
65	QG-5	0.1666	0.1659	-0.0360	0.1670	0.1661
66	QG-6	0.0000	NA	0.1202	0.0212	0.0022
67	QG-7	-0.1090	-0.1109	-0.1201	-0.1087	-0.1103
68	QG-8	0.0611	NA	0.0616	0.0727	0.0632
69	QG-9	0.0000	NA	0.0015	0.0000	0.0006
70	QG-10	-0.0200	-0.0207	-0.0220	-0.0207	-0.0201
71	QG-11	0.1606	NA	0.1575	0.1559	0.1578
72	QG-12	-0.0750	NA	-0.0548	-0.0957	-0.0779
73	QG-13	0.1045	NA	0.1036	0.1036	0.1031

74	QG-14	-0.0160	-0.0163	-0.0146	-0.0163	-0.0158
75	QG-15	-0.0250	-0.0255	-0.0253	-0.0255	-0.0250
76	QG-16	-0.0180	-0.0180	-0.0176	-0.0180	-0.0185
77	QG-17	-0.0580	NA	-0.0640	-0.0513	-0.0581
78	QG-18	-0.0090	-0.0087	-0.0100	-0.0087	-0.0083
79	QG-19	-0.0340	-0.0348	-0.0353	-0.0348	-0.0343
80	QG-20	-0.0070	NA	-0.0083	-0.0116	-0.0075
81	QG-21	-0.1120	-0.1106	-0.1083	-0.1106	-0.1101
82	QG-22	0.0000	NA	0.0074	0.0209	0.0009
83	QG-23	-0.0160	NA	-0.0139	-0.0036	-0.0160
84	QG-24	-0.0670	-0.0666	-0.0615	-0.0342	-0.0670
85	QG-25	0.0000	NA	-0.0223	-0.0944	-0.0004
86	QG-26	-0.0230	NA	-0.0145	0.0040	-0.0222
87	QG-27	0.0000	NA	-0.0091	0.0332	-0.0006
88	QG-28	0.0000	NA	-0.0286	-0.0460	-0.0028
89	QG-29	-0.0090	NA	-0.0019	-0.0050	-0.0089
90	QG-30	-0.0190	-0.0190	-0.0184	-0.0190	-0.0195
91	PF 1-2	1.7331	NA	1.7319	1.7331	1.7343
92	PF 1-3	0.8765	0.8707	0.8765	0.8765	0.8772
93	PF 2-4	0.4365	0.4395	0.4365	0.4365	0.4370
94	PF 3-4	0.8214	NA	0.8212	0.8214	0.8217
95	PF 2-5	0.8236	-0.8199	0.5775	0.8216	0.8218
96	PF 2-6	0.6038	NA	0.5901	0.6045	0.6040
97	PF 4-6	0.7213	0.7291	0.6646	0.7242	0.7203
98	PF 5-7	-0.1478	-0.1474	0.0188	-0.1442	-0.1446
99	PF 6-7	0.3813	0.3870	0.1332	0.3803	0.3812
100	PF 6-8	0.2956	0.2917	0.2924	0.2917	0.2921
101	PF 6-9	0.2772	0.2717	0.2853	0.2796	0.2786
102	PF 6-10	0.1584	0.1596	0.1630	0.1598	0.1593
103	PF 9-11	0.0000	NA	0.0000	0.0000	0.0000
104	PF 9-10	0.2772	NA	0.2853	0.2796	0.2792
105	PF 4-12	0.4419	NA	0.4655	0.4400	0.4449
106	PF 12-13	0.0000	NA	0.0000	0.0000	0.0000
107	PF 12-14	0.0786	0.0800	0.0765	0.0777	0.0781
108	PF 12-15	0.1789	NA	0.1692	0.1788	0.1775
109	PF 12-16	0.0724	0.0727	0.0626	0.0727	0.0716
110	PF 14-15	0.0158	0.0156	0.0137	0.0156	0.0155
111	PF 16-17	0.0369	NA	0.0224	0.0373	0.0357
112	PF 15-18	0.0602	0.0593	0.0551	0.0601	0.0594
113	PF 18-19	0.0278	0.0281	0.0238	0.0276	0.0274
114	PF 19-20	-0.0673	NA	-0.0705	-0.0669	-0.0675
115	PF 10-20	0.0903	NA	0.0969	0.0911	0.0905
116	PF 10-17	0.0533	0.0536	0.0563	0.0536	0.0541
117	PF 10-21	0.1579	NA	0.1602	0.1604	0.1594
118	PF 10-22	0.0762	NA	0.0773	0.0773	0.0769
119	PF 21-22	-0.0183	NA	-0.0182	-0.0184	-0.0189
120	PF 15-23	0.0504	NA	0.0444	0.0508	0.0505
121	PF 22-24	0.0574	0.0580	0.0608	0.0580	0.0578
122	PF 23-24	0.0180	0.0179	0.0135	0.0177	0.0174
123	PF 24-25	-0.0121	-0.0118	-0.0114	-0.0104	-0.0113
124	PF 25-26	0.0354	0.0357	0.0343	0.0357	0.0352
125	PF 25-27	-0.0476	-0.0480	-0.0493	-0.0480	-0.0475

126	PF 28-27	0.1807	0.1793	0.1825	0.1793	0.1837
127	PF 27-29	0.0619	NA	0.0619	0.0615	0.0621
128	PF 27-30	0.0709	0.0722	0.0710	0.0706	0.0711
129	PF 29-30	0.0370	0.0371	0.0372	0.0371	0.0371
130	PF 8-28	-0.0054	NA	-0.0040	-0.0053	-0.0058
131	PF 6-28	0.1867	NA	0.1882	0.1828	0.1829
132	PT 2-1	-1.6809	-1.6536	-1.6799	-1.6809	-1.6821
133	PT 3-1	-0.8454	NA	-0.8454	-0.8454	-0.8461
134	PT 4-2	-0.4263	NA	-0.4263	-0.4263	-0.4268
135	PT 4-3	-0.8129	-0.8014	-0.8127	-0.8129	-0.8131
136	PT 5-2	-0.7942	NA	-0.5627	-0.7923	-0.7925
137	PT 6-2	-0.5843	-0.5796	-0.5715	-0.5850	-0.5846
138	PT 6-4	-0.7150	NA	-0.6592	-0.7178	-0.7140
139	PT 7-5	0.1495	NA	-0.0188	0.1459	0.1463
140	PT 7-6	-0.3775	NA	-0.1326	-0.3765	-0.3774
141	PT 8-6	-0.2946	NA	-0.2913	-0.2906	-0.2911
142	PT 9-6	-0.2772	NA	-0.2853	-0.2796	-0.2786
143	PT 10-6	-0.1584	NA	-0.1630	-0.1598	-0.1593
144	PT 11-9	0.0000	NA	0.0000	0.0000	0.0000
145	PT 10-9	-0.2772	-0.2796	-0.2853	-0.2796	-0.2792
146	PT 12-4	-0.4419	-0.4497	-0.4655	-0.4400	-0.4449
147	PT 13-12	0.0000	NA	0.0000	0.0000	0.0000
148	PT 14-12	-0.0778	NA	-0.0758	-0.0770	-0.0774
149	PT 15-12	-0.1767	-0.1733	-0.1672	-0.1767	-0.1754
150	PT 16-12	-0.0719	NA	-0.0621	-0.0722	-0.0711
151	PT 15-14	-0.0158	NA	-0.0137	-0.0156	-0.0155
152	PT 17-16	-0.0368	NA	-0.0223	-0.0372	-0.0356
153	PT 18-15	-0.0598	NA	-0.0548	-0.0597	-0.0591
154	PT 19-18	-0.0277	NA	-0.0237	-0.0275	-0.0274
155	PT 20-19	0.0674	0.0687	0.0706	0.0670	0.0677
156	PT 20-10	-0.0894	-0.0902	-0.0960	-0.0902	-0.0897
157	PT 17-10	-0.0532	NA	-0.0561	-0.0534	-0.0539
158	PT 21-10	-0.1567	-0.1564	-0.1591	-0.1593	-0.1583
159	PT 22-10	-0.0757	NA	-0.0768	-0.0768	-0.0763
160	PT 22-21	0.0183	0.0184	0.0182	0.0184	0.0189
161	PT 23-15	-0.0500	-0.0507	-0.0441	-0.0506	-0.0502
162	PT 24-22	-0.0569	-0.0568	-0.0603	-0.0575	-0.0573
163	PT 24-23	-0.0180	-0.0177	-0.0135	-0.0177	-0.0174
164	PT 25-24	0.0122	NA	0.0116	0.0110	0.0114
165	PT 26-25	-0.0350	NA	-0.0340	-0.0354	-0.0347
166	PT 27-25	0.0479	NA	0.0496	0.0484	0.0478
167	PT 27-28	-0.1807	-0.1842	-0.1825	-0.1793	-0.1837
168	PT 29-27	-0.0610	NA	-0.0611	-0.0607	-0.0612
169	PT 30-27	-0.0693	NA	-0.0694	-0.0690	-0.0695
170	PT 30-29	-0.0367	-0.0367	-0.0369	-0.0367	-0.0368
171	PT 28-8	0.0055	0.0054	0.0041	0.0054	0.0058
172	PT 28-6	-0.1862	NA	-0.1876	-0.1822	-0.1823
173	QF 1-2	-0.2470	NA	-0.2409	-0.2470	-0.2478
174	QF 1-3	0.0428	0.0421	0.0427	0.0428	0.0434
175	QF 2-4	0.0475	0.0481	0.0451	0.0475	0.0485
176	QF 3-4	-0.0385	NA	-0.0396	-0.0385	-0.0371
177	QF 2-5	0.0278	0.0268	0.0726	0.0268	0.0281

178	QF 2-6	0.0137	NA	0.0106	0.0136	0.0148
179	QF 4-6	-0.1591	-0.1583	-0.1608	-0.1596	-0.1587
180	QF 5-7	0.1149	0.1149	0.0183	0.1149	0.1154
181	QF 6-7	-0.0278	-0.0284	0.0660	-0.0284	-0.0271
182	QF 6-8	-0.0720	-0.0736	-0.0662	-0.0736	-0.0731
183	QF 6-9	-0.0809	-0.0822	-0.0833	-0.0868	-0.0796
184	QF 6-10	0.0019	NA	0.0002	-0.0024	0.0022
185	QF 9-11	-0.1560	-0.1516	-0.1531	-0.1516	-0.1534
186	QF 9-10	0.0588	NA	0.0540	0.0480	0.0580
187	QF 4-12	0.1441	NA	0.1387	0.1456	0.1474
188	QF 12-13	-0.1032	-0.1023	-0.1023	-0.1023	-0.1018
189	QF 12-14	0.0240	0.0237	0.0248	0.0215	0.0237
190	QF 12-15	0.0679	NA	0.0722	0.0578	0.0670
191	QF 12-16	0.0335	0.0335	0.0381	0.0262	0.0330
192	QF 14-15	0.0065	0.0063	0.0087	0.0038	0.0064
193	QF 16-17	0.0144	NA	0.0195	0.0071	0.0134
194	QF 15-18	0.0160	0.0153	0.0202	0.0153	0.0155
195	QF 18-19	0.0062	0.0059	0.0096	0.0058	0.0064
196	QF 19-20	-0.0279	NA	-0.0258	-0.0291	-0.0280
197	QF 10-20	0.0371	NA	0.0365	0.0430	0.0376
198	QF 10-17	0.0443	0.0449	0.0451	0.0449	0.0454
199	QF 10-21	0.1001	NA	0.0943	0.0870	0.0985
200	QF 10-22	0.0460	NA	0.0428	0.0376	0.0452
201	QF 21-22	-0.0143	NA	-0.0163	-0.0259	-0.0140
202	QF 15-23	0.0291	NA	0.0314	0.0166	0.0286
203	QF 22-24	0.0306	0.0295	0.0328	0.0315	0.0310
204	QF 23-24	0.0124	0.0125	0.0170	0.0125	0.0120
205	QF 24-25	0.0201	0.0196	0.0325	0.0541	0.0201
206	QF 25-26	0.0237	0.0233	0.0150	-0.0035	0.0228
207	QF 25-27	-0.0037	-0.0038	-0.0052	-0.0376	-0.0033
208	QF 28-27	0.0504	0.0519	0.0536	0.0470	0.0514
209	QF 27-29	0.0167	NA	0.0113	0.0137	0.0168
210	QF 27-30	0.0166	0.0173	0.0142	0.0155	0.0169
211	QF 29-30	0.0061	0.0060	0.0078	0.0072	0.0063
212	QF 8-28	-0.0054	NA	0.0009	0.0046	-0.0044
213	QF 6-27	0.0011	NA	0.0268	0.0339	0.0038
214	QT 2-1	0.3447	0.3363	0.3382	0.3447	0.3454
215	QT 3-1	0.0265	NA	0.0267	0.0265	0.0260
216	QT 4-2	-0.0554	NA	-0.0530	-0.0554	-0.0564
217	QT 4-3	0.0544	0.0525	0.0555	0.0544	0.0530
218	QT 5-2	0.0517	NA	-0.0543	0.0521	0.0507
219	QT 6-2	0.0058	0.0060	0.0063	0.0060	0.0047
220	QT 6-4	0.1719	NA	0.1704	0.1725	0.1714
221	QT 7-5	-0.1313	NA	-0.0387	-0.1314	-0.1319
222	QT 7-6	0.0223	NA	-0.0814	0.0228	0.0216
223	QT 8-6	0.0666	NA	0.0607	0.0681	0.0676
224	QT 9-6	0.0972	NA	0.1005	0.1035	0.0960
225	QT 10-6	0.0110	NA	0.0134	0.0155	0.0107
226	QT 11-9	0.1606	NA	0.1575	0.1559	0.1578
227	QT 10-9	-0.0508	-0.0521	-0.0457	-0.0400	-0.0499
228	QT 12-4	-0.0972	-0.1004	-0.0875	-0.0990	-0.0998
229	QT 13-12	0.1045	NA	0.1036	0.1036	0.1031

230	QT 14-12	-0.0225	NA	-0.0233	-0.0201	-0.0222
231	QT 15-12	-0.0636	-0.0629	-0.0682	-0.0537	-0.0628
232	QT 16-12	-0.0324	NA	-0.0371	-0.0251	-0.0319
233	QT 15-14	-0.0064	NA	-0.0087	-0.0037	-0.0063
234	QT 17-16	-0.0141	NA	-0.0194	-0.0068	-0.0131
235	QT 18-15	-0.0152	NA	-0.0195	-0.0146	-0.0147
236	QT 19-18	-0.0061	NA	-0.0095	-0.0057	-0.0063
237	QT 20-19	0.0283	0.0282	0.0262	0.0294	0.0283
238	QT 20-10	-0.0353	-0.0363	-0.0345	-0.0410	-0.0358
239	QT 17-10	-0.0439	NA	-0.0447	-0.0445	-0.0450
240	QT 21-10	-0.0977	-0.0957	-0.0919	-0.0847	-0.0961
241	QT 22-10	-0.0449	NA	-0.0417	-0.0366	-0.0442
242	QT 22-21	0.0143	0.0145	0.0163	0.0260	0.0140
243	QT 23-15	-0.0284	-0.0285	-0.0309	-0.0160	-0.0280
244	QT 24-22	-0.0299	-0.0308	-0.0320	-0.0308	-0.0303
245	QT 24-23	-0.0123	-0.0124	-0.0169	-0.0124	-0.0119
246	QT 25-24	-0.0200	NA	-0.0321	-0.0532	-0.0199
247	QT 26-25	-0.0230	NA	-0.0145	0.0040	-0.0222
248	QT 27-25	0.0042	NA	0.0057	0.0384	0.0038
249	QT 27-28	-0.0375	-0.0379	-0.0403	-0.0344	-0.0381
250	QT 29-27	-0.0151	NA	-0.0097	-0.0122	-0.0152
251	QT 30-27	-0.0136	NA	-0.0112	-0.0125	-0.0138
252	QT 30-29	-0.0054	-0.0054	-0.0071	-0.0066	-0.0057
253	QT 28-8	-0.0380	-0.0395	-0.0443	-0.0479	-0.0391
254	QT 28-6	-0.0123	N/A	-0.0379	-0.0451	-0.0151

B.2.3. Single Bad-Data as Power Injection Meter

Table B.3 IEEE 30 Bus System - Single Bad-Data as Power Injection Meter

IEEE 30 bus system - Single Bad-Data at PG 2						
Sr	Type	Actual	Measurement	Estimated		
				WLS	WLAV	LMR
1	Vm-1	1.0600	1.0600	1.0600	1.0600	1.0605
2	Vm-2	1.0450	NA	1.0444	1.0450	1.0455
3	Vm-3	1.0212	1.0212	1.0212	1.0212	1.0217
4	Vm-4	1.0123	1.0133	1.0124	1.0123	1.0128
5	Vm-5	1.0100	1.0176	1.0091	1.0102	1.0105
6	Vm-6	1.0106	NA	1.0109	1.0106	1.0112
7	Vm-7	1.0026	NA	1.0026	1.0026	1.0030
8	Vm-8	1.0100	1.0010	1.0101	1.0101	1.0106
9	Vm-9	1.0511	NA	1.0523	1.0518	1.0514
10	Vm-10	1.0454	1.0491	1.0472	1.0469	1.0457
11	Vm-11	1.0820	NA	1.0827	1.0818	1.0817
12	Vm-12	1.0573	1.0557	1.0597	1.0575	1.0572
13	Vm-13	1.0710	NA	1.0733	1.0710	1.0707
14	Vm-14	1.0425	NA	1.0449	1.0430	1.0425

15	Vm-15	1.0379	NA	1.0403	1.0387	1.0380
16	Vm-16	1.0446	NA	1.0469	1.0455	1.0446
17	Vm-17	1.0402	NA	1.0419	1.0416	1.0404
18	Vm-18	1.0284	1.0294	1.0302	1.0294	1.0286
19	Vm-19	1.0259	NA	1.0275	1.0270	1.0261
20	Vm-20	1.0300	NA	1.0315	1.0312	1.0302
21	Vm-21	1.0330	1.0431	1.0352	1.0349	1.0334
22	Vm-22	1.0335	NA	1.0358	1.0356	1.0339
23	Vm-23	1.0274	NA	1.0298	1.0293	1.0276
24	Vm-24	1.0218	1.0252	1.0234	1.0238	1.0222
25	Vm-25	1.0176	1.0098	1.0150	1.0098	1.0178
26	Vm-26	0.9999	1.0022	1.0009	1.0022	1.0005
27	Vm-27	1.0235	NA	1.0214	1.0215	1.0236
28	Vm-28	1.0071	1.0052	1.0061	1.0052	1.0075
29	Vm-29	1.0037	1.0042	1.0038	1.0042	1.0037
30	Vm-30	0.9922	NA	0.9915	0.9917	0.9921
31	PG-1	2.6096	2.6103	2.6121	2.6096	2.6120
32	PG-2	0.1830	-0.1822	0.1047	0.1796	0.1658
33	PG-3	-0.0240	NA	-0.0241	-0.0240	-0.0216
34	PG-4	-0.0760	-0.0751	-0.1079	-0.0751	-0.0746
35	PG-5	-0.9420	-0.9366	-0.8549	-0.9366	-0.9370
36	PG-6	0.0000	NA	0.0327	-0.0008	0.0061
37	PG-7	-0.2280	-0.2306	-0.2148	-0.2306	-0.2311
38	PG-8	-0.3000	NA	-0.2955	-0.2959	-0.2968
39	PG-9	0.0000	NA	0.0000	0.0000	0.0006
40	PG-10	-0.0580	-0.0571	-0.0576	-0.0571	-0.0572
41	PG-11	0.0000	NA	0.0000	0.0000	0.0000
42	PG-12	-0.1120	NA	-0.1554	-0.1219	-0.1172
43	PG-13	0.0000	NA	0.0000	0.0000	0.0000
44	PG-14	-0.0620	-0.0613	-0.0621	-0.0613	-0.0619
45	PG-15	-0.0820	-0.0813	-0.0813	-0.0813	-0.0808
46	PG-16	-0.0350	-0.0349	-0.0396	-0.0349	-0.0354
47	PG-17	-0.0900	NA	-0.0789	-0.0883	-0.0895
48	PG-18	-0.0320	-0.0322	-0.0311	-0.0322	-0.0317
49	PG-19	-0.0950	-0.0944	-0.0943	-0.0952	-0.0949
50	PG-20	-0.0220	NA	-0.0252	-0.0215	-0.0220
51	PG-21	-0.1750	-0.1780	-0.1773	-0.1777	-0.1775
52	PG-22	0.0000	NA	0.0023	-0.0005	0.0002
53	PG-23	-0.0320	NA	-0.0307	-0.0307	-0.0328
54	PG-24	-0.0870	-0.0856	-0.0852	-0.0856	-0.0860
55	PG-25	0.0000	NA	-0.0034	-0.0017	-0.0009
56	PG-26	-0.0350	NA	-0.0340	-0.0354	-0.0347
57	PG-27	0.0000	NA	-0.0002	0.0012	-0.0027
58	PG-28	0.0000	NA	-0.0004	0.0025	0.0066
59	PG-29	-0.0240	-0.0236	-0.0238	-0.0236	-0.0241
60	PG-30	-0.1060	-0.1057	-0.1062	-0.1057	-0.1062
61	QG-1	-0.2042	-0.2064	-0.1951	-0.2042	-0.2047
62	QG-2	0.4337	0.4435	0.4268	0.4331	0.4364
63	QG-3	-0.0120	NA	-0.0129	-0.0120	-0.0113
64	QG-4	-0.0160	-0.0154	-0.0115	-0.0154	-0.0148
65	QG-5	0.1666	0.1659	0.1214	0.1666	0.1656
66	QG-6	0.0000	NA	0.0263	0.0237	0.0023

67	QG-7	-0.1090	-0.1109	-0.1095	-0.1086	-0.1103
68	QG-8	0.0611	NA	0.0611	0.0728	0.0633
69	QG-9	0.0000	NA	0.0018	0.0000	0.0006
70	QG-10	-0.0200	-0.0207	-0.0217	-0.0207	-0.0201
71	QG-11	0.1606	NA	0.1578	0.1559	0.1575
72	QG-12	-0.0750	NA	-0.0507	-0.0806	-0.0780
73	QG-13	0.1045	NA	0.1036	0.1036	0.1031
74	QG-14	-0.0160	-0.0163	-0.0146	-0.0163	-0.0158
75	QG-15	-0.0250	-0.0255	-0.0252	-0.0255	-0.0250
76	QG-16	-0.0180	-0.0180	-0.0171	-0.0180	-0.0185
77	QG-17	-0.0580	NA	-0.0649	-0.0560	-0.0581
78	QG-18	-0.0090	-0.0087	-0.0103	-0.0087	-0.0083
79	QG-19	-0.0340	-0.0348	-0.0354	-0.0348	-0.0343
80	QG-20	-0.0070	NA	-0.0080	-0.0070	-0.0075
81	QG-21	-0.1120	-0.1106	-0.1081	-0.1106	-0.1101
82	QG-22	0.0000	NA	0.0077	0.0120	0.0009
83	QG-23	-0.0160	NA	-0.0141	-0.0112	-0.0160
84	QG-24	-0.0670	-0.0666	-0.0616	-0.0387	-0.0670
85	QG-25	0.0000	NA	-0.0223	-0.0836	-0.0004
86	QG-26	-0.0230	NA	-0.0145	0.0040	-0.0222
87	QG-27	0.0000	NA	-0.0089	0.0190	-0.0006
88	QG-28	0.0000	NA	-0.0247	-0.0428	-0.0035
89	QG-29	-0.0090	NA	-0.0018	-0.0005	-0.0089
90	QG-30	-0.0190	-0.0190	-0.0183	-0.0190	-0.0195
91	PF 1-2	1.7331	NA	1.7357	1.7331	1.7379
92	PF 1-3	0.8765	0.8707	0.8764	0.8765	0.8741
93	PF 2-4	0.4365	0.4395	0.4350	0.4365	0.4328
94	PF 3-4	0.8214	NA	0.8212	0.8214	0.8216
95	PF 2-5	0.8236	0.8199	0.7646	0.8210	0.8194
96	PF 2-6	0.6038	NA	0.5886	0.6031	0.5991
97	PF 4-6	0.7213	0.7291	0.6648	0.7182	0.7169
98	PF 5-7	-0.1478	-0.1474	-0.1158	-0.1449	-0.1467
99	PF 6-7	0.3813	0.3870	0.3346	0.3809	0.3833
100	PF 6-8	0.2956	0.2917	0.2923	0.2917	0.2921
101	PF 6-9	0.2772	0.2717	0.2849	0.2796	0.2786
102	PF 6-10	0.1584	0.1596	0.1628	0.1598	0.1593
103	PF 9-11	0.0000	NA	0.0000	0.0000	0.0000
104	PF 9-10	0.2772	NA	0.2849	0.2796	0.2792
105	PF 4-12	0.4419	NA	0.4649	0.4459	0.4443
106	PF 12-13	0.0000	NA	0.0000	0.0000	0.0000
107	PF 12-14	0.0786	0.0800	0.0767	0.0774	0.0781
108	PF 12-15	0.1789	NA	0.1697	0.1764	0.1775
109	PF 12-16	0.0724	0.0727	0.0630	0.0703	0.0716
110	PF 14-15	0.0158	0.0156	0.0139	0.0153	0.0155
111	PF 16-17	0.0369	NA	0.0229	0.0349	0.0357
112	PF 15-18	0.0602	0.0593	0.0555	0.0593	0.0594
113	PF 18-19	0.0278	0.0281	0.0240	0.0268	0.0274
114	PF 19-20	-0.0673	NA	-0.0703	-0.0685	-0.0676
115	PF 10-20	0.0903	NA	0.0966	0.0910	0.0905
116	PF 10-17	0.0533	0.0536	0.0562	0.0536	0.0541
117	PF 10-21	0.1579	NA	0.1601	0.1604	0.1597
118	PF 10-22	0.0762	NA	0.0772	0.0774	0.0770

119	PF 21-22	-0.0183	NA	-0.0183	-0.0184	-0.0189
120	PF 15-23	0.0504	NA	0.0448	0.0489	0.0505
121	PF 22-24	0.0574	0.0580	0.0607	0.0580	0.0578
122	PF 23-24	0.0180	0.0179	0.0138	0.0179	0.0174
123	PF 24-25	-0.0121	-0.0118	-0.0112	-0.0102	-0.0113
124	PF 25-26	0.0354	0.0357	0.0343	0.0357	0.0352
125	PF 25-27	-0.0476	-0.0480	-0.0492	-0.0480	-0.0475
126	PF 28-27	0.1807	0.1793	0.1824	0.1793	0.1837
127	PF 27-29	0.0619	NA	0.0619	0.0615	0.0621
128	PF 27-30	0.0709	0.0722	0.0710	0.0706	0.0711
129	PF 29-30	0.0370	0.0371	0.0372	0.0371	0.0371
130	PF 8-28	-0.0054	NA	-0.0042	-0.0053	-0.0057
131	PF 6-28	0.1867	NA	0.1877	0.1828	0.1833
132	PT 2-1	-1.6809	-1.6536	-1.6835	-1.6809	-1.6855
133	PT 3-1	-0.8454	NA	-0.8453	-0.8454	-0.8432
134	PT 4-2	-0.4263	NA	-0.4249	-0.4263	-0.4228
135	PT 4-3	-0.8129	-0.8014	-0.8126	-0.8129	-0.8130
136	PT 5-2	-0.7942	NA	-0.7391	-0.7917	-0.7903
137	PT 6-2	-0.5843	-0.5796	-0.5701	-0.5837	-0.5799
138	PT 6-4	-0.7150	NA	-0.6594	-0.7120	-0.7107
139	PT 7-5	0.1495	NA	0.1169	0.1465	0.1484
140	PT 7-6	-0.3775	NA	-0.3316	-0.3771	-0.3795
141	PT 8-6	-0.2946	NA	-0.2913	-0.2906	-0.2911
142	PT 9-6	-0.2772	NA	-0.2849	-0.2796	-0.2786
143	PT 10-6	-0.1584	NA	-0.1628	-0.1598	-0.1593
144	PT 11-9	0.0000	NA	0.0000	0.0000	0.0000
145	PT 10-9	-0.2772	-0.2796	-0.2849	-0.2796	-0.2792
146	PT 12-4	-0.4419	-0.4497	-0.4649	-0.4459	-0.4443
147	PT 13-12	0.0000	NA	0.0000	0.0000	0.0000
148	PT 14-12	-0.0778	NA	-0.0760	-0.0767	-0.0774
149	PT 15-12	-0.1767	-0.1733	-0.1677	-0.1743	-0.1753
150	PT 16-12	-0.0719	NA	-0.0625	-0.0698	-0.0710
151	PT 15-14	-0.0158	NA	-0.0138	-0.0153	-0.0155
152	PT 17-16	-0.0368	NA	-0.0229	-0.0349	-0.0356
153	PT 18-15	-0.0598	NA	-0.0551	-0.0589	-0.0590
154	PT 19-18	-0.0277	NA	-0.0240	-0.0267	-0.0273
155	PT 20-19	0.0674	0.0687	0.0705	0.0687	0.0677
156	PT 20-10	-0.0894	-0.0902	-0.0957	-0.0902	-0.0897
157	PT 17-10	-0.0532	NA	-0.0560	-0.0534	-0.0539
158	PT 21-10	-0.1567	-0.1564	-0.1590	-0.1593	-0.1586
159	PT 22-10	-0.0757	NA	-0.0767	-0.0768	-0.0765
160	PT 22-21	0.0183	0.0184	0.0183	0.0184	0.0189
161	PT 23-15	-0.0500	-0.0507	-0.0445	-0.0486	-0.0502
162	PT 24-22	-0.0569	-0.0568	-0.0602	-0.0575	-0.0573
163	PT 24-23	-0.0180	-0.0177	-0.0138	-0.0179	-0.0174
164	PT 25-24	0.0122	NA	0.0114	0.0107	0.0114
165	PT 26-25	-0.0350	NA	-0.0340	-0.0354	-0.0347
166	PT 27-25	0.0479	NA	0.0494	0.0484	0.0478
167	PT 27-28	-0.1807	-0.1842	-0.1824	-0.1793	-0.1837
168	PT 29-27	-0.0610	NA	-0.0611	-0.0607	-0.0612
169	PT 30-27	-0.0693	NA	-0.0694	-0.0690	-0.0695
170	PT 30-29	-0.0367	-0.0367	-0.0369	-0.0367	-0.0368

171	PT 28-8	0.0055	0.0054	0.0043	0.0054	0.0057
172	PT 28-6	-0.1862	NA	-0.1871	-0.1822	-0.1827
173	QF 1-2	-0.2470	NA	-0.2378	-0.2470	-0.2475
174	QF 1-3	0.0428	0.0421	0.0427	0.0428	0.0428
175	QF 2-4	0.0475	0.0481	0.0442	0.0475	0.0482
176	QF 3-4	-0.0385	NA	-0.0396	-0.0385	-0.0371
177	QF 2-5	0.0278	0.0268	0.0348	0.0270	0.0279
178	QF 2-6	0.0137	NA	0.0120	0.0139	0.0145
179	QF 4-6	-0.1591	-0.1583	-0.1510	-0.1583	-0.1585
180	QF 5-7	0.1149	0.1149	0.0934	0.1149	0.1154
181	QF 6-7	-0.0278	-0.0284	-0.0101	-0.0284	-0.0269
182	QF 6-8	-0.0720	-0.0736	-0.0667	-0.0736	-0.0731
183	QF 6-9	-0.0809	-0.0822	-0.0849	-0.0840	-0.0794
184	QF 6-10	0.0019	NA	-0.0006	-0.0008	0.0023
185	QF 9-11	-0.1560	-0.1516	-0.1534	-0.1516	-0.1531
186	QF 9-10	0.0588	NA	0.0530	0.0510	0.0579
187	QF 4-12	0.1441	NA	0.1364	0.1438	0.1474
188	QF 12-13	-0.1032	-0.1023	-0.1023	-0.1023	-0.1018
189	QF 12-14	0.0240	0.0237	0.0250	0.0232	0.0237
190	QF 12-15	0.0679	NA	0.0732	0.0639	0.0670
191	QF 12-16	0.0335	0.0335	0.0389	0.0308	0.0330
192	QF 14-15	0.0065	0.0063	0.0089	0.0054	0.0064
193	QF 16-17	0.0144	NA	0.0208	0.0117	0.0134
194	QF 15-18	0.0160	0.0153	0.0208	0.0154	0.0155
195	QF 18-19	0.0062	0.0059	0.0098	0.0059	0.0064
196	QF 19-20	-0.0279	NA	-0.0257	-0.0290	-0.0280
197	QF 10-20	0.0371	NA	0.0360	0.0382	0.0376
198	QF 10-17	0.0443	0.0449	0.0446	0.0449	0.0454
199	QF 10-21	0.1001	NA	0.0940	0.0924	0.0985
200	QF 10-22	0.0460	NA	0.0426	0.0412	0.0452
201	QF 21-22	-0.0143	NA	-0.0165	-0.0206	-0.0140
202	QF 15-23	0.0291	NA	0.0320	0.0242	0.0286
203	QF 22-24	0.0306	0.0295	0.0327	0.0315	0.0310
204	QF 23-24	0.0124	0.0125	0.0174	0.0125	0.0120
205	QF 24-25	0.0201	0.0196	0.0326	0.0495	0.0201
206	QF 25-26	0.0237	0.0233	0.0150	-0.0035	0.0228
207	QF 25-27	-0.0037	-0.0038	-0.0051	-0.0313	-0.0033
208	QF 28-27	0.0504	0.0519	0.0532	0.0505	0.0514
209	QF 27-29	0.0167	NA	0.0112	0.0105	0.0168
210	QF 27-30	0.0166	0.0173	0.0142	0.0142	0.0169
211	QF 29-30	0.0061	0.0060	0.0078	0.0084	0.0063
212	QF 8-28	-0.0054	NA	0.0000	0.0047	-0.0043
213	QF 6-27	0.0011	NA	0.0234	0.0341	0.0044
214	QT 2-1	0.3447	0.3363	0.3358	0.3447	0.3458
215	QT 3-1	0.0265	NA	0.0267	0.0265	0.0258
216	QT 4-2	-0.0554	NA	-0.0523	-0.0554	-0.0567
217	QT 4-3	0.0544	0.0525	0.0555	0.0544	0.0530
218	QT 5-2	0.0517	NA	0.0280	0.0517	0.0502
219	QT 6-2	0.0058	0.0060	0.0046	0.0055	0.0041
220	QT 6-4	0.1719	NA	0.1605	0.1709	0.1710
221	QT 7-5	-0.1313	NA	-0.1113	-0.1314	-0.1318
222	QT 7-6	0.0223	NA	0.0018	0.0228	0.0215

223	QT 8-6	0.0666	NA	0.0611	0.0681	0.0676
224	QT 9-6	0.0972	NA	0.1021	0.1006	0.0958
225	QT 10-6	0.0110	NA	0.0142	0.0139	0.0107
226	QT 11-9	0.1606	NA	0.1578	0.1559	0.1575
227	QT 10-9	-0.0508	-0.0521	-0.0447	-0.0429	-0.0498
228	QT 12-4	-0.0972	-0.1004	-0.0855	-0.0962	-0.0999
229	QT 13-12	0.1045	NA	0.1036	0.1036	0.1031
230	QT 14-12	-0.0225	NA	-0.0236	-0.0217	-0.0222
231	QT 15-12	-0.0636	-0.0629	-0.0692	-0.0598	-0.0628
232	QT 16-12	-0.0324	NA	-0.0380	-0.0298	-0.0319
233	QT 15-14	-0.0064	NA	-0.0089	-0.0054	-0.0063
234	QT 17-16	-0.0141	NA	-0.0207	-0.0115	-0.0131
235	QT 18-15	-0.0152	NA	-0.0201	-0.0147	-0.0147
236	QT 19-18	-0.0061	NA	-0.0098	-0.0058	-0.0063
237	QT 20-19	0.0283	0.0282	0.0260	0.0293	0.0283
238	QT 20-10	-0.0353	-0.0363	-0.0340	-0.0363	-0.0358
239	QT 17-10	-0.0439	NA	-0.0442	-0.0445	-0.0450
240	QT 21-10	-0.0977	-0.0957	-0.0916	-0.0901	-0.0961
241	QT 22-10	-0.0449	NA	-0.0415	-0.0401	-0.0441
242	QT 22-21	0.0143	0.0145	0.0165	0.0206	0.0140
243	QT 23-15	-0.0284	-0.0285	-0.0315	-0.0237	-0.0280
244	QT 24-22	-0.0299	-0.0308	-0.0319	-0.0308	-0.0303
245	QT 24-23	-0.0123	-0.0124	-0.0172	-0.0124	-0.0119
246	QT 25-24	-0.0200	NA	-0.0322	-0.0487	-0.0199
247	QT 26-25	-0.0230	NA	-0.0145	0.0040	-0.0222
248	QT 27-25	0.0042	NA	0.0056	0.0320	0.0038
249	QT 27-28	-0.0375	-0.0379	-0.0400	-0.0377	-0.0381
250	QT 29-27	-0.0151	NA	-0.0096	-0.0090	-0.0152
251	QT 30-27	-0.0136	NA	-0.0112	-0.0112	-0.0138
252	QT 30-29	-0.0054	-0.0054	-0.0072	-0.0078	-0.0057
253	QT 28-8	-0.0380	-0.0395	-0.0434	-0.0480	-0.0393
254	QT 28-6	-0.0123	N/A	-0.0345	-0.0452	-0.0156

B.2.4. Single Bad-Data as Voltage Magnitude Meter

Table B.4 IEEE 30 Bus System - Single Bad-Data as Voltage Magnitude Meter

IEEE 30 bus system - Single Bad-Data at Vm 12						
Sr	Type	Actual	Measurement	Estimated		
				WLS	WLAV	LMR
1	Vm-1	1.0600	1.0600	1.0600	1.0600	1.0610
2	Vm-2	1.0450	NA	1.0450	1.0450	1.0460
3	Vm-3	1.0212	1.0212	1.0212	1.0212	1.0221
4	Vm-4	1.0123	1.0133	1.0123	1.0123	1.0132
5	Vm-5	1.0100	1.0176	1.0100	1.0102	1.0110
6	Vm-6	1.0106	NA	1.0097	1.0106	1.0115
7	Vm-7	1.0026	NA	1.0020	1.0026	1.0034

8	Vm-8	1.0100	1.0010	1.0089	1.0101	1.0109
9	Vm-9	1.0511	NA	1.0542	1.0530	1.0517
10	Vm-10	1.0454	1.0491	1.0499	1.0488	1.0461
11	Vm-11	1.0820	NA	1.0851	1.0830	1.0818
12	Vm-12	1.0573	1.1057	1.0692	1.0608	1.0576
13	Vm-13	1.0710	NA	1.0826	1.0743	1.0711
14	Vm-14	1.0425	NA	1.0532	1.0459	1.0429
15	Vm-15	1.0379	NA	1.0474	1.0413	1.0384
16	Vm-16	1.0446	NA	1.0537	1.0481	1.0450
17	Vm-17	1.0402	NA	1.0451	1.0437	1.0408
18	Vm-18	1.0284	1.0294	1.0351	1.0315	1.0290
19	Vm-19	1.0259	NA	1.0318	1.0291	1.0265
20	Vm-20	1.0300	NA	1.0356	1.0332	1.0306
21	Vm-21	1.0330	1.0431	1.0381	1.0373	1.0338
22	Vm-22	1.0335	NA	1.0387	1.0379	1.0343
23	Vm-23	1.0274	NA	1.0346	1.0307	1.0280
24	Vm-24	1.0218	1.0252	1.0264	1.0252	1.0226
25	Vm-25	1.0176	1.0098	1.0160	1.0098	1.0182
26	Vm-26	0.9999	1.0022	1.0011	1.0022	1.0009
27	Vm-27	1.0235	NA	1.0225	1.0239	1.0241
28	Vm-28	1.0071	1.0052	1.0056	1.0052	1.0079
29	Vm-29	1.0037	1.0042	1.0040	1.0042	1.0037
30	Vm-30	0.9922	NA	0.9920	0.9927	0.9923
31	PG-1	2.6096	2.6103	2.6094	2.6096	2.6124
32	PG-2	0.1830	0.1822	0.1819	0.1797	0.1806
33	PG-3	-0.0240	NA	-0.0241	-0.0240	-0.0246
34	PG-4	-0.0760	-0.0751	-0.0696	-0.0751	-0.0747
35	PG-5	-0.9420	-0.9366	-0.9379	-0.9366	-0.9370
36	PG-6	0.0000	NA	-0.0167	-0.0014	-0.0051
37	PG-7	-0.2280	-0.2306	-0.2326	-0.2306	-0.2311
38	PG-8	-0.3000	NA	-0.2982	-0.2959	-0.2969
39	PG-9	0.0000	NA	0.0000	0.0000	0.0006
40	PG-10	-0.0580	-0.0571	-0.0569	-0.0571	-0.0576
41	PG-11	0.0000	NA	0.0000	0.0000	0.0000
42	PG-12	-0.1120	NA	-0.1118	-0.1159	-0.1178
43	PG-13	0.0000	NA	0.0000	0.0000	0.0000
44	PG-14	-0.0620	-0.0613	-0.0616	-0.0613	-0.0619
45	PG-15	-0.0820	-0.0813	-0.0804	-0.0813	-0.0808
46	PG-16	-0.0350	-0.0349	-0.0341	-0.0349	-0.0354
47	PG-17	-0.0900	NA	-0.0925	-0.0903	-0.0896
48	PG-18	-0.0320	-0.0322	-0.0330	-0.0322	-0.0317
49	PG-19	-0.0950	-0.0944	-0.0957	-0.0944	-0.0949
50	PG-20	-0.0220	NA	-0.0206	-0.0236	-0.0220
51	PG-21	-0.1750	-0.1780	-0.1766	-0.1778	-0.1772
52	PG-22	0.0000	NA	0.0027	-0.0005	0.0003
53	PG-23	-0.0320	NA	-0.0328	-0.0328	-0.0328
54	PG-24	-0.0870	-0.0856	-0.0845	-0.0856	-0.0860
55	PG-25	0.0000	NA	-0.0054	-0.0016	-0.0009
56	PG-26	-0.0350	NA	-0.0342	-0.0354	-0.0347
57	PG-27	0.0000	NA	-0.0008	0.0014	-0.0027
58	PG-28	0.0000	NA	0.0119	0.0025	0.0069
59	PG-29	-0.0240	-0.0236	-0.0239	-0.0236	-0.0241

60	PG-30	-0.1060	-0.1057	-0.1063	-0.1058	-0.1062
61	QG-1	-0.2042	-0.2064	-0.2039	-0.2042	-0.2045
62	QG-2	0.4337	0.4435	0.4387	0.4331	0.4367
63	QG-3	-0.0120	NA	-0.0127	-0.0120	-0.0111
64	QG-4	-0.0160	-0.0154	-0.0409	-0.0295	-0.0148
65	QG-5	0.1666	0.1659	0.1702	0.1666	0.1659
66	QG-6	0.0000	NA	-0.0483	0.0136	0.0024
67	QG-7	-0.1090	-0.1109	-0.1089	-0.1086	-0.1108
68	QG-8	0.0611	NA	0.0600	0.0728	0.0630
69	QG-9	0.0000	NA	0.0053	0.0000	0.0006
70	QG-10	-0.0200	-0.0207	-0.0182	-0.0207	-0.0201
71	QG-11	0.1606	NA	0.1615	0.1559	0.1564
72	QG-12	-0.0750	NA	0.0124	-0.0581	-0.0777
73	QG-13	0.1045	NA	0.1036	0.1036	0.1031
74	QG-14	-0.0160	-0.0163	-0.0161	-0.0163	-0.0158
75	QG-15	-0.0250	-0.0255	-0.0245	-0.0255	-0.0250
76	QG-16	-0.0180	-0.0180	-0.0107	-0.0180	-0.0185
77	QG-17	-0.0580	NA	-0.0745	-0.0571	-0.0577
78	QG-18	-0.0090	-0.0087	-0.0157	-0.0102	-0.0084
79	QG-19	-0.0340	-0.0348	-0.0369	-0.0348	-0.0343
80	QG-20	-0.0070	NA	-0.0058	-0.0070	-0.0075
81	QG-21	-0.1120	-0.1106	-0.1078	-0.0987	-0.1101
82	QG-22	0.0000	NA	0.0102	0.0129	0.0012
83	QG-23	-0.0160	NA	-0.0176	-0.0160	-0.0160
84	QG-24	-0.0670	-0.0666	-0.0640	-0.0394	-0.0671
85	QG-25	0.0000	NA	-0.0263	-0.0999	-0.0004
86	QG-26	-0.0230	NA	-0.0161	0.0040	-0.0222
87	QG-27	0.0000	NA	0.0005	0.0459	0.0008
88	QG-28	0.0000	NA	-0.0158	-0.0491	-0.0019
89	QG-29	-0.0090	NA	-0.0047	-0.0089	-0.0102
90	QG-30	-0.0190	-0.0190	-0.0187	-0.0190	-0.0195
91	PF 1-2	1.7331	NA	1.7329	1.7331	1.7348
92	PF 1-3	0.8765	0.8707	0.8765	0.8765	0.8776
93	PF 2-4	0.4365	0.4395	0.4365	0.4365	0.4372
94	PF 3-4	0.8214	NA	0.8213	0.8214	0.8219
95	PF 2-5	0.8236	0.8199	0.8227	0.8210	0.8218
96	PF 2-6	0.6038	NA	0.6035	0.6032	0.6043
97	PF 4-6	0.7213	0.7291	0.7206	0.7186	0.7206
98	PF 5-7	-0.1478	-0.1474	-0.1445	-0.1448	-0.1445
99	PF 6-7	0.3813	0.3870	0.3826	0.3809	0.3810
100	PF 6-8	0.2956	0.2917	0.2915	0.2917	0.2921
101	PF 6-9	0.2772	0.2717	0.2747	0.2796	0.2786
102	PF 6-10	0.1584	0.1596	0.1569	0.1598	0.1593
103	PF 9-11	0.0000	NA	0.0000	0.0000	0.0000
104	PF 9-10	0.2772	NA	0.2747	0.2796	0.2792
105	PF 4-12	0.4419	NA	0.4489	0.4455	0.4450
106	PF 12-13	0.0000	NA	0.0000	0.0000	0.0000
107	PF 12-14	0.0786	0.0800	0.0801	0.0783	0.0781
108	PF 12-15	0.1789	NA	0.1824	0.1789	0.1775
109	PF 12-16	0.0724	0.0727	0.0746	0.0724	0.0716
110	PF 14-15	0.0158	0.0156	0.0177	0.0162	0.0155
111	PF 16-17	0.0369	NA	0.0398	0.0370	0.0357

112	PF 15-18	0.0602	0.0593	0.0630	0.0605	0.0594
113	PF 18-19	0.0278	0.0281	0.0295	0.0280	0.0274
114	PF 19-20	-0.0673	NA	-0.0662	-0.0665	-0.0675
115	PF 10-20	0.0903	NA	0.0877	0.0910	0.0905
116	PF 10-17	0.0533	0.0536	0.0529	0.0536	0.0541
117	PF 10-21	0.1579	NA	0.1580	0.1604	0.1594
118	PF 10-22	0.0762	NA	0.0760	0.0773	0.0769
119	PF 21-22	-0.0183	NA	-0.0197	-0.0184	-0.0189
120	PF 15-23	0.0504	NA	0.0542	0.0510	0.0505
121	PF 22-24	0.0574	0.0580	0.0585	0.0580	0.0578
122	PF 23-24	0.0180	0.0179	0.0210	0.0179	0.0174
123	PF 24-25	-0.0121	-0.0118	-0.0055	-0.0103	-0.0113
124	PF 25-26	0.0354	0.0357	0.0346	0.0357	0.0352
125	PF 25-27	-0.0476	-0.0480	-0.0457	-0.0480	-0.0475
126	PF 28-27	0.1807	0.1793	0.1797	0.1793	0.1836
127	PF 27-29	0.0619	NA	0.0619	0.0615	0.0621
128	PF 27-30	0.0709	0.0722	0.0710	0.0707	0.0711
129	PF 29-30	0.0370	0.0371	0.0372	0.0371	0.0371
130	PF 8-28	-0.0054	NA	-0.0077	-0.0053	-0.0058
131	PF 6-28	0.1867	NA	0.1759	0.1828	0.1831
132	PT 2-1	-1.6809	-1.6536	-1.6808	-1.6809	-1.6827
133	PT 3-1	-0.8454	NA	-0.8454	-0.8454	-0.8465
134	PT 4-2	-0.4263	NA	-0.4264	-0.4263	-0.4270
135	PT 4-3	-0.8129	-0.8014	-0.8128	-0.8129	-0.8134
136	PT 5-2	-0.7942	NA	-0.7933	-0.7918	-0.7926
137	PT 6-2	-0.5843	-0.5796	-0.5840	-0.5837	-0.5848
138	PT 6-4	-0.7150	NA	-0.7144	-0.7124	-0.7143
139	PT 7-5	0.1495	NA	0.1462	0.1465	0.1461
140	PT 7-6	-0.3775	NA	-0.3788	-0.3771	-0.3772
141	PT 8-6	-0.2946	NA	-0.2905	-0.2906	-0.2911
142	PT 9-6	-0.2772	NA	-0.2747	-0.2796	-0.2786
143	PT 10-6	-0.1584	NA	-0.1569	-0.1598	-0.1593
144	PT 11-9	0.0000	NA	0.0000	0.0000	0.0000
145	PT 10-9	-0.2772	-0.2796	-0.2747	-0.2796	-0.2792
146	PT 12-4	-0.4419	-0.4497	-0.4489	-0.4455	-0.4450
147	PT 13-12	0.0000	NA	0.0000	0.0000	0.0000
148	PT 14-12	-0.0778	NA	-0.0794	-0.0775	-0.0774
149	PT 15-12	-0.1767	-0.1733	-0.1800	-0.1768	-0.1754
150	PT 16-12	-0.0719	NA	-0.0739	-0.0719	-0.0711
151	PT 15-14	-0.0158	NA	-0.0176	-0.0161	-0.0155
152	PT 17-16	-0.0368	NA	-0.0397	-0.0369	-0.0356
153	PT 18-15	-0.0598	NA	-0.0626	-0.0601	-0.0591
154	PT 19-18	-0.0277	NA	-0.0295	-0.0279	-0.0274
155	PT 20-19	0.0674	0.0687	0.0664	0.0666	0.0677
156	PT 20-10	-0.0894	-0.0902	-0.0869	-0.0902	-0.0897
157	PT 17-10	-0.0532	NA	-0.0528	-0.0534	-0.0539
158	PT 21-10	-0.1567	-0.1564	-0.1570	-0.1594	-0.1583
159	PT 22-10	-0.0757	NA	-0.0755	-0.0768	-0.0763
160	PT 22-21	0.0183	0.0184	0.0197	0.0184	0.0189
161	PT 23-15	-0.0500	-0.0507	-0.0538	-0.0507	-0.0502
162	PT 24-22	-0.0569	-0.0568	-0.0581	-0.0575	-0.0573
163	PT 24-23	-0.0180	-0.0177	-0.0209	-0.0179	-0.0174

164	PT 25-24	0.0122	NA	0.0058	0.0108	0.0114
165	PT 26-25	-0.0350	NA	-0.0342	-0.0354	-0.0347
166	PT 27-25	0.0479	NA	0.0459	0.0485	0.0478
167	PT 27-28	-0.1807	-0.1842	-0.1797	-0.1793	-0.1836
168	PT 29-27	-0.0610	NA	-0.0611	-0.0607	-0.0612
169	PT 30-27	-0.0693	NA	-0.0694	-0.0691	-0.0695
170	PT 30-29	-0.0367	-0.0367	-0.0369	-0.0367	-0.0367
171	PT 28-8	0.0055	0.0054	0.0077	0.0054	0.0058
172	PT 28-6	-0.1862	NA	-0.1754	-0.1822	-0.1825
173	QF 1-2	-0.2470	NA	-0.2468	-0.2470	-0.2478
174	QF 1-3	0.0428	0.0421	0.0428	0.0428	0.0433
175	QF 2-4	0.0475	0.0481	0.0472	0.0475	0.0484
176	QF 3-4	-0.0385	NA	-0.0393	-0.0385	-0.0371
177	QF 2-5	0.0278	0.0268	0.0279	0.0270	0.0282
178	QF 2-6	0.0137	NA	0.0191	0.0139	0.0147
179	QF 4-6	-0.1591	-0.1583	-0.1354	-0.1583	-0.1587
180	QF 5-7	0.1149	0.1149	0.1190	0.1149	0.1154
181	QF 6-7	-0.0278	-0.0284	-0.0319	-0.0284	-0.0267
182	QF 6-8	-0.0720	-0.0736	-0.0681	-0.0736	-0.0731
183	QF 6-9	-0.0809	-0.0822	-0.1008	-0.0903	-0.0793
184	QF 6-10	0.0019	NA	-0.0086	-0.0045	0.0022
185	QF 9-11	-0.1560	-0.1516	-0.1569	-0.1516	-0.1521
186	QF 9-10	0.0588	NA	0.0446	0.0444	0.0570
187	QF 4-12	0.1441	NA	0.0945	0.1297	0.1473
188	QF 12-13	-0.1032	-0.1023	-0.1023	-0.1023	-0.1018
189	QF 12-14	0.0240	0.0237	0.0286	0.0244	0.0237
190	QF 12-15	0.0679	NA	0.0867	0.0693	0.0670
191	QF 12-16	0.0335	0.0335	0.0482	0.0335	0.0330
192	QF 14-15	0.0065	0.0063	0.0109	0.0066	0.0064
193	QF 16-17	0.0144	NA	0.0362	0.0144	0.0134
194	QF 15-18	0.0160	0.0153	0.0286	0.0169	0.0156
195	QF 18-19	0.0062	0.0059	0.0119	0.0059	0.0064
196	QF 19-20	-0.0279	NA	-0.0252	-0.0290	-0.0280
197	QF 10-20	0.0371	NA	0.0329	0.0382	0.0376
198	QF 10-17	0.0443	0.0449	0.0392	0.0434	0.0450
199	QF 10-21	0.1001	NA	0.0929	0.0865	0.0983
200	QF 10-22	0.0460	NA	0.0420	0.0392	0.0451
201	QF 21-22	-0.0143	NA	-0.0171	-0.0145	-0.0142
202	QF 15-23	0.0291	NA	0.0398	0.0291	0.0286
203	QF 22-24	0.0306	0.0295	0.0340	0.0366	0.0310
204	QF 23-24	0.0124	0.0125	0.0214	0.0125	0.0120
205	QF 24-25	0.0201	0.0196	0.0357	0.0540	0.0201
206	QF 25-26	0.0237	0.0233	0.0166	-0.0035	0.0228
207	QF 25-27	-0.0037	-0.0038	-0.0077	-0.0433	-0.0033
208	QF 28-27	0.0504	0.0519	0.0490	0.0440	0.0514
209	QF 27-29	0.0167	NA	0.0134	0.0166	0.0178
210	QF 27-30	0.0166	0.0173	0.0152	0.0166	0.0173
211	QF 29-30	0.0061	0.0060	0.0071	0.0061	0.0059
212	QF 8-28	-0.0054	NA	-0.0027	0.0046	-0.0046
213	QF 6-27	0.0011	NA	0.0128	0.0340	0.0031
214	QT 2-1	0.3447	0.3363	0.3444	0.3447	0.3454
215	QT 3-1	0.0265	NA	0.0266	0.0265	0.0261

216	QT 4-2	-0.0554	NA	-0.0551	-0.0554	-0.0563
217	QT 4-3	0.0544	0.0525	0.0551	0.0544	0.0530
218	QT 5-2	0.0517	NA	0.0513	0.0517	0.0505
219	QT 6-2	0.0058	0.0060	0.0004	0.0055	0.0047
220	QT 6-4	0.1719	NA	0.1478	0.1709	0.1714
221	QT 7-5	-0.1313	NA	-0.1353	-0.1314	-0.1319
222	QT 7-6	0.0223	NA	0.0265	0.0228	0.0211
223	QT 8-6	0.0666	NA	0.0626	0.0681	0.0676
224	QT 9-6	0.0972	NA	0.1175	0.1071	0.0956
225	QT 10-6	0.0110	NA	0.0212	0.0175	0.0108
226	QT 11-9	0.1606	NA	0.1615	0.1559	0.1564
227	QT 10-9	-0.0508	-0.0521	-0.0370	-0.0365	-0.0490
228	QT 12-4	-0.0972	-0.1004	-0.0488	-0.0830	-0.0997
229	QT 13-12	0.1045	NA	0.1036	0.1036	0.1031
230	QT 14-12	-0.0225	NA	-0.0270	-0.0229	-0.0222
231	QT 15-12	-0.0636	-0.0629	-0.0821	-0.0650	-0.0628
232	QT 16-12	-0.0324	NA	-0.0468	-0.0324	-0.0319
233	QT 15-14	-0.0064	NA	-0.0108	-0.0065	-0.0064
234	QT 17-16	-0.0141	NA	-0.0357	-0.0141	-0.0131
235	QT 18-15	-0.0152	NA	-0.0276	-0.0161	-0.0148
236	QT 19-18	-0.0061	NA	-0.0118	-0.0058	-0.0063
237	QT 20-19	0.0283	0.0282	0.0255	0.0293	0.0283
238	QT 20-10	-0.0353	-0.0363	-0.0313	-0.0363	-0.0358
239	QT 17-10	-0.0439	NA	-0.0388	-0.0431	-0.0446
240	QT 21-10	-0.0977	-0.0957	-0.0906	-0.0842	-0.0959
241	QT 22-10	-0.0449	NA	-0.0410	-0.0382	-0.0440
242	QT 22-21	0.0143	0.0145	0.0172	0.0145	0.0142
243	QT 23-15	-0.0284	-0.0285	-0.0390	-0.0285	-0.0280
244	QT 24-22	-0.0299	-0.0308	-0.0332	-0.0358	-0.0303
245	QT 24-23	-0.0123	-0.0124	-0.0211	-0.0124	-0.0119
246	QT 25-24	-0.0200	NA	-0.0353	-0.0531	-0.0199
247	QT 26-25	-0.0230	NA	-0.0161	0.0040	-0.0222
248	QT 27-25	0.0042	NA	0.0081	0.0441	0.0038
249	QT 27-28	-0.0375	-0.0379	-0.0363	-0.0315	-0.0381
250	QT 29-27	-0.0151	NA	-0.0118	-0.0150	-0.0162
251	QT 30-27	-0.0136	NA	-0.0122	-0.0136	-0.0142
252	QT 30-29	-0.0054	-0.0054	-0.0065	-0.0054	-0.0053
253	QT 28-8	-0.0380	-0.0395	-0.0407	-0.0480	-0.0389
254	QT 28-6	-0.0123	N/A	-0.0241	-0.0452	-0.0144

B.2.5. Multiple Non-Interacting Bad-Data

Table B.5 IEEE 30 Bus System – Multiple Non-Interacting Bad-Data

IEEE 30 bus system - Multiple Non-Interacting Bad-Data at PF 2-4, PG 5, Vm 12						
Sr	Type	Actual	Measurement	Estimated		
				WLS	WLAV	LMR
1	Vm-1	1.0600	1.0600	1.0600	1.0600	1.0609
2	Vm-2	1.0450	NA	1.0455	1.0450	1.0459
3	Vm-3	1.0212	1.0212	1.0212	1.0212	1.0220

4	Vm-4	1.0123	1.0133	1.0123	1.0123	1.0131
5	Vm-5	1.0100	1.0176	1.0349	1.0103	1.0110
6	Vm-6	1.0106	NA	1.0084	1.0106	1.0114
7	Vm-7	1.0026	NA	1.0045	1.0027	1.0033
8	Vm-8	1.0100	1.0010	1.0077	1.0101	1.0108
9	Vm-9	1.0511	NA	1.0543	1.0530	1.0516
10	Vm-10	1.0454	1.0491	1.0503	1.0488	1.0460
11	Vm-11	1.0820	NA	1.0856	1.0830	1.0819
12	Vm-12	1.0573	1.1057	1.0680	1.0607	1.0575
13	Vm-13	1.0710	NA	1.0814	1.0742	1.0710
14	Vm-14	1.0425	NA	1.0522	1.0459	1.0428
15	Vm-15	1.0379	NA	1.0466	1.0412	1.0383
16	Vm-16	1.0446	NA	1.0531	1.0480	1.0449
17	Vm-17	1.0402	NA	1.0457	1.0435	1.0407
18	Vm-18	1.0284	1.0294	1.0350	1.0317	1.0289
19	Vm-19	1.0259	NA	1.0321	1.0291	1.0264
20	Vm-20	1.0300	NA	1.0361	1.0332	1.0305
21	Vm-21	1.0330	1.0431	1.0386	1.0374	1.0337
22	Vm-22	1.0335	NA	1.0392	1.0379	1.0342
23	Vm-23	1.0274	NA	1.0342	1.0307	1.0279
24	Vm-24	1.0218	1.0252	1.0265	1.0252	1.0225
25	Vm-25	1.0176	1.0098	1.0162	1.0098	1.0181
26	Vm-26	0.9999	1.0022	1.0012	1.0022	1.0008
27	Vm-27	1.0235	NA	1.0228	1.0239	1.0239
28	Vm-28	1.0071	1.0052	1.0051	1.0052	1.0078
29	Vm-29	1.0037	1.0042	1.0040	1.0042	1.0037
30	Vm-30	0.9922	NA	0.9921	0.9927	0.9923
31	PG-1	2.6096	2.6103	2.6071	2.6096	2.6124
32	PG-2	0.1830	0.1822	-0.2522	0.1787	0.1806
33	PG-3	-0.0240	NA	-0.0239	-0.0240	-0.0248
34	PG-4	-0.0760	-0.0751	-0.0283	-0.0751	-0.0747
35	PG-5	-0.9420	0.9366	0.0580	-0.9344	-0.9350
36	PG-6	0.0000	NA	-0.3886	-0.0029	-0.0094
37	PG-7	-0.2280	-0.2306	-0.5251	-0.2306	-0.2311
38	PG-8	-0.3000	NA	-0.3000	-0.2959	-0.2966
39	PG-9	0.0000	NA	0.0000	0.0000	0.0006
40	PG-10	-0.0580	-0.0571	-0.0561	-0.0571	-0.0576
41	PG-11	0.0000	NA	0.0000	0.0000	0.0000
42	PG-12	-0.1120	NA	-0.0704	-0.1155	-0.1165
43	PG-13	0.0000	NA	0.0000	0.0000	0.0000
44	PG-14	-0.0620	-0.0613	-0.0614	-0.0613	-0.0619
45	PG-15	-0.0820	-0.0813	-0.0797	-0.0813	-0.0808
46	PG-16	-0.0350	-0.0349	-0.0297	-0.0349	-0.0354
47	PG-17	-0.0900	NA	-0.1031	-0.0904	-0.0898
48	PG-18	-0.0320	-0.0322	-0.0338	-0.0322	-0.0317
49	PG-19	-0.0950	-0.0944	-0.0965	-0.0944	-0.0949
50	PG-20	-0.0220	NA	-0.0168	-0.0236	-0.0222
51	PG-21	-0.1750	-0.1780	-0.1760	-0.1778	-0.1767
52	PG-22	0.0000	NA	0.0036	-0.0005	0.0005
53	PG-23	-0.0320	NA	-0.0338	-0.0328	-0.0327
54	PG-24	-0.0870	-0.0856	-0.0840	-0.0856	-0.0861
55	PG-25	0.0000	NA	-0.0064	-0.0016	-0.0009

56	PG-26	-0.0350	NA	-0.0343	-0.0354	-0.0347
57	PG-27	0.0000	NA	-0.0012	0.0014	-0.0023
58	PG-28	0.0000	NA	0.0205	0.0025	0.0071
59	PG-29	-0.0240	-0.0236	-0.0239	-0.0236	-0.0241
60	PG-30	-0.1060	-0.1057	-0.1063	-0.1058	-0.1062
61	QG-1	-0.2042	-0.2064	-0.2123	-0.2042	-0.2045
62	QG-2	0.4337	0.4435	0.3865	0.4329	0.4361
63	QG-3	-0.0120	NA	-0.0112	-0.0120	-0.0110
64	QG-4	-0.0160	-0.0154	-0.0291	-0.0288	-0.0148
65	QG-5	0.1666	0.1659	0.1235	0.1665	0.1662
66	QG-6	0.0000	NA	-0.0486	0.0133	0.0018
67	QG-7	-0.1090	-0.1109	-0.1220	-0.1087	-0.1103
68	QG-8	0.0611	NA	0.0589	0.0727	0.0630
69	QG-9	0.0000	NA	0.0074	0.0000	0.0006
70	QG-10	-0.0200	-0.0207	-0.0149	-0.0207	-0.0201
71	QG-11	0.1606	NA	0.1638	0.1559	0.1575
72	QG-12	-0.0750	NA	-0.0110	-0.0596	-0.0779
73	QG-13	0.1045	NA	0.1036	0.1036	0.1031
74	QG-14	-0.0160	-0.0163	-0.0169	-0.0163	-0.0158
75	QG-15	-0.0250	-0.0255	-0.0252	-0.0255	-0.0250
76	QG-16	-0.0180	-0.0180	-0.0128	-0.0180	-0.0185
77	QG-17	-0.0580	NA	-0.0631	-0.0586	-0.0580
78	QG-18	-0.0090	-0.0087	-0.0146	-0.0087	-0.0083
79	QG-19	-0.0340	-0.0348	-0.0359	-0.0348	-0.0343
80	QG-20	-0.0070	NA	-0.0048	-0.0077	-0.0075
81	QG-21	-0.1120	-0.1106	-0.1069	-0.0978	-0.1101
82	QG-22	0.0000	NA	0.0150	0.0136	0.0008
83	QG-23	-0.0160	NA	-0.0170	-0.0158	-0.0160
84	QG-24	-0.0670	-0.0666	-0.0647	-0.0396	-0.0671
85	QG-25	0.0000	NA	-0.0261	-0.0999	-0.0004
86	QG-26	-0.0230	NA	-0.0164	0.0040	-0.0222
87	QG-27	0.0000	NA	0.0059	0.0459	0.0003
88	QG-28	0.0000	NA	-0.0060	-0.0489	-0.0022
89	QG-29	-0.0090	NA	-0.0057	-0.0089	-0.0098
90	QG-30	-0.0190	-0.0190	-0.0188	-0.0190	-0.0195
91	PF 1-2	1.7331	NA	1.7306	1.7331	1.7346
92	PF 1-3	0.8765	0.8707	0.8765	0.8765	0.8778
93	PF 2-4	0.4365	-0.4395	0.4378	0.4365	0.4374
94	PF 3-4	0.8214	NA	0.8215	0.8214	0.8219
95	PF 2-5	0.8236	0.8199	0.3681	0.8199	0.8209
96	PF 2-6	0.6038	NA	0.6205	0.6032	0.6048
97	PF 4-6	0.7213	0.7291	0.7866	0.7189	0.7217
98	PF 5-7	-0.1478	-0.1474	0.4202	-0.1437	-0.1432
99	PF 6-7	0.3813	0.3870	0.1133	0.3797	0.3797
100	PF 6-8	0.2956	0.2917	0.2910	0.2917	0.2918
101	PF 6-9	0.2772	0.2717	0.2663	0.2796	0.2781
102	PF 6-10	0.1584	0.1596	0.1521	0.1598	0.1591
103	PF 9-11	0.0000	NA	0.0000	0.0000	0.0000
104	PF 9-10	0.2772	NA	0.2663	0.2796	0.2787
105	PF 4-12	0.4419	NA	0.4256	0.4452	0.4442
106	PF 12-13	0.0000	NA	0.0000	0.0000	0.0000
107	PF 12-14	0.0786	0.0800	0.0815	0.0782	0.0782

108	PF 12-15	0.1789	NA	0.1901	0.1790	0.1776
109	PF 12-16	0.0724	0.0727	0.0836	0.0725	0.0719
110	PF 14-15	0.0158	0.0156	0.0193	0.0162	0.0156
111	PF 16-17	0.0369	NA	0.0532	0.0370	0.0360
112	PF 15-18	0.0602	0.0593	0.0674	0.0605	0.0596
113	PF 18-19	0.0278	0.0281	0.0330	0.0280	0.0276
114	PF 19-20	-0.0673	NA	-0.0636	-0.0664	-0.0673
115	PF 10-20	0.0903	NA	0.0812	0.0910	0.0905
116	PF 10-17	0.0533	0.0536	0.0501	0.0536	0.0541
117	PF 10-21	0.1579	NA	0.1561	0.1604	0.1590
118	PF 10-22	0.0762	NA	0.0748	0.0773	0.0766
119	PF 21-22	-0.0183	NA	-0.0209	-0.0184	-0.0189
120	PF 15-23	0.0504	NA	0.0598	0.0510	0.0505
121	PF 22-24	0.0574	0.0580	0.0570	0.0580	0.0577
122	PF 23-24	0.0180	0.0179	0.0255	0.0179	0.0176
123	PF 24-25	-0.0121	-0.0118	-0.0021	-0.0103	-0.0113
124	PF 25-26	0.0354	0.0357	0.0346	0.0357	0.0352
125	PF 25-27	-0.0476	-0.0480	-0.0434	-0.0480	-0.0475
126	PF 28-27	0.1807	0.1793	0.1778	0.1793	0.1832
127	PF 27-29	0.0619	NA	0.0620	0.0615	0.0621
128	PF 27-30	0.0709	0.0722	0.0710	0.0707	0.0711
129	PF 29-30	0.0370	0.0371	0.0372	0.0371	0.0371
130	PF 8-28	-0.0054	NA	-0.0101	-0.0053	-0.0059
131	PF 6-28	0.1867	NA	0.1678	0.1828	0.1825
132	PT 2-1	-1.6809	-1.6536	-1.6786	-1.6809	-1.6825
133	PT 3-1	-0.8454	NA	-0.8454	-0.8454	-0.8467
134	PT 4-2	-0.4263	NA	-0.4275	-0.4263	-0.4272
135	PT 4-3	-0.8129	-0.8014	-0.8130	-0.8129	-0.8133
136	PT 5-2	-0.7942	NA	-0.3622	-0.7907	-0.7918
137	PT 6-2	-0.5843	-0.5796	-0.5999	-0.5838	-0.5853
138	PT 6-4	-0.7150	NA	-0.7793	-0.7127	-0.7154
139	PT 7-5	0.1495	NA	-0.4121	0.1453	0.1448
140	PT 7-6	-0.3775	NA	-0.1130	-0.3759	-0.3759
141	PT 8-6	-0.2946	NA	-0.2899	-0.2906	-0.2908
142	PT 9-6	-0.2772	NA	-0.2663	-0.2796	-0.2781
143	PT 10-6	-0.1584	NA	-0.1521	-0.1598	-0.1591
144	PT 11-9	0.0000	NA	0.0000	0.0000	0.0000
145	PT 10-9	-0.2772	-0.2796	-0.2663	-0.2796	-0.2787
146	PT 12-4	-0.4419	-0.4497	-0.4256	-0.4452	-0.4442
147	PT 13-12	0.0000	NA	0.0000	0.0000	0.0000
148	PT 14-12	-0.0778	NA	-0.0807	-0.0775	-0.0774
149	PT 15-12	-0.1767	-0.1733	-0.1876	-0.1768	-0.1755
150	PT 16-12	-0.0719	NA	-0.0829	-0.0719	-0.0714
151	PT 15-14	-0.0158	NA	-0.0192	-0.0161	-0.0155
152	PT 17-16	-0.0368	NA	-0.0530	-0.0370	-0.0359
153	PT 18-15	-0.0598	NA	-0.0669	-0.0601	-0.0592
154	PT 19-18	-0.0277	NA	-0.0329	-0.0279	-0.0275
155	PT 20-19	0.0674	0.0687	0.0637	0.0666	0.0675
156	PT 20-10	-0.0894	-0.0902	-0.0805	-0.0902	-0.0897
157	PT 17-10	-0.0532	NA	-0.0500	-0.0534	-0.0539
158	PT 21-10	-0.1567	-0.1564	-0.1551	-0.1594	-0.1578
159	PT 22-10	-0.0757	NA	-0.0744	-0.0768	-0.0761

160	PT 22-21	0.0183	0.0184	0.0209	0.0184	0.0189
161	PT 23-15	-0.0500	-0.0507	-0.0593	-0.0507	-0.0502
162	PT 24-22	-0.0569	-0.0568	-0.0565	-0.0575	-0.0573
163	PT 24-23	-0.0180	-0.0177	-0.0254	-0.0179	-0.0175
164	PT 25-24	0.0122	NA	0.0023	0.0108	0.0114
165	PT 26-25	-0.0350	NA	-0.0343	-0.0354	-0.0347
166	PT 27-25	0.0479	NA	0.0436	0.0485	0.0478
167	PT 27-28	-0.1807	-0.1842	-0.1778	-0.1793	-0.1832
168	PT 29-27	-0.0610	NA	-0.0611	-0.0607	-0.0612
169	PT 30-27	-0.0693	NA	-0.0694	-0.0691	-0.0695
170	PT 30-29	-0.0367	-0.0367	-0.0369	-0.0367	-0.0368
171	PT 28-8	0.0055	0.0054	0.0101	0.0054	0.0059
172	PT 28-6	-0.1862	NA	-0.1674	-0.1822	-0.1820
173	QF 1-2	-0.2470	NA	-0.2551	-0.2470	-0.2478
174	QF 1-3	0.0428	0.0421	0.0428	0.0428	0.0433
175	QF 2-4	0.0475	0.0481	0.0502	0.0475	0.0484
176	QF 3-4	-0.0385	NA	-0.0378	-0.0385	-0.0371
177	QF 2-5	0.0278	0.0268	-0.0421	0.0268	0.0276
178	QF 2-6	0.0137	NA	0.0258	0.0140	0.0147
179	QF 4-6	-0.1591	-0.1583	-0.1219	-0.1581	-0.1587
180	QF 5-7	0.1149	0.1149	0.1021	0.1149	0.1154
181	QF 6-7	-0.0278	-0.0284	0.0031	-0.0284	-0.0273
182	QF 6-8	-0.0720	-0.0736	-0.0696	-0.0736	-0.0731
183	QF 6-9	-0.0809	-0.0822	-0.1083	-0.0903	-0.0796
184	QF 6-10	0.0019	NA	-0.0121	-0.0045	0.0022
185	QF 9-11	-0.1560	-0.1516	-0.1590	-0.1516	-0.1531
186	QF 9-10	0.0588	NA	0.0420	0.0445	0.0578
187	QF 4-12	0.1441	NA	0.0971	0.1302	0.1472
188	QF 12-13	-0.1032	-0.1023	-0.1023	-0.1023	-0.1018
189	QF 12-14	0.0240	0.0237	0.0269	0.0242	0.0237
190	QF 12-15	0.0679	NA	0.0795	0.0685	0.0670
191	QF 12-16	0.0335	0.0335	0.0406	0.0335	0.0330
192	QF 14-15	0.0065	0.0063	0.0083	0.0064	0.0064
193	QF 16-17	0.0144	NA	0.0262	0.0144	0.0134
194	QF 15-18	0.0160	0.0153	0.0229	0.0162	0.0155
195	QF 18-19	0.0062	0.0059	0.0073	0.0066	0.0064
196	QF 19-20	-0.0279	NA	-0.0287	-0.0283	-0.0280
197	QF 10-20	0.0371	NA	0.0354	0.0382	0.0376
198	QF 10-17	0.0443	0.0449	0.0378	0.0449	0.0453
199	QF 10-21	0.1001	NA	0.0912	0.0855	0.0985
200	QF 10-22	0.0460	NA	0.0410	0.0387	0.0453
201	QF 21-22	-0.0143	NA	-0.0179	-0.0145	-0.0140
202	QF 15-23	0.0291	NA	0.0348	0.0289	0.0286
203	QF 22-24	0.0306	0.0295	0.0372	0.0368	0.0310
204	QF 23-24	0.0124	0.0125	0.0170	0.0125	0.0120
205	QF 24-25	0.0201	0.0196	0.0337	0.0540	0.0201
206	QF 25-26	0.0237	0.0233	0.0170	-0.0035	0.0228
207	QF 25-27	-0.0037	-0.0038	-0.0097	-0.0433	-0.0033
208	QF 28-27	0.0504	0.0519	0.0464	0.0440	0.0514
209	QF 27-29	0.0167	NA	0.0142	0.0166	0.0175
210	QF 27-30	0.0166	0.0173	0.0156	0.0166	0.0172
211	QF 29-30	0.0061	0.0060	0.0069	0.0061	0.0060

212	QF 8-28	-0.0054	NA	-0.0052	0.0046	-0.0046
213	QF 6-27	0.0011	NA	0.0027	0.0338	0.0033
214	QT 2-1	0.3447	0.3363	0.3525	0.3447	0.3454
215	QT 3-1	0.0265	NA	0.0266	0.0265	0.0262
216	QT 4-2	-0.0554	NA	-0.0580	-0.0554	-0.0563
217	QT 4-3	0.0544	0.0525	0.0537	0.0544	0.0530
218	QT 5-2	0.0517	NA	0.0215	0.0516	0.0508
219	QT 6-2	0.0058	0.0060	-0.0028	0.0055	0.0049
220	QT 6-4	0.1719	NA	0.1383	0.1707	0.1715
221	QT 7-5	-0.1313	NA	-0.1028	-0.1314	-0.1320
222	QT 7-6	0.0223	NA	-0.0193	0.0227	0.0216
223	QT 8-6	0.0666	NA	0.0641	0.0681	0.0676
224	QT 9-6	0.0972	NA	0.1244	0.1071	0.0959
225	QT 10-6	0.0110	NA	0.0241	0.0175	0.0107
226	QT 11-9	0.1606	NA	0.1638	0.1559	0.1575
227	QT 10-9	-0.0508	-0.0521	-0.0348	-0.0365	-0.0497
228	QT 12-4	-0.0972	-0.1004	-0.0557	-0.0836	-0.0998
229	QT 13-12	0.1045	NA	0.1036	0.1036	0.1031
230	QT 14-12	-0.0225	NA	-0.0252	-0.0227	-0.0222
231	QT 15-12	-0.0636	-0.0629	-0.0747	-0.0643	-0.0628
232	QT 16-12	-0.0324	NA	-0.0391	-0.0324	-0.0319
233	QT 15-14	-0.0064	NA	-0.0082	-0.0064	-0.0063
234	QT 17-16	-0.0141	NA	-0.0256	-0.0141	-0.0131
235	QT 18-15	-0.0152	NA	-0.0219	-0.0154	-0.0147
236	QT 19-18	-0.0061	NA	-0.0071	-0.0065	-0.0063
237	QT 20-19	0.0283	0.0282	0.0291	0.0286	0.0283
238	QT 20-10	-0.0353	-0.0363	-0.0339	-0.0363	-0.0358
239	QT 17-10	-0.0439	NA	-0.0375	-0.0445	-0.0449
240	QT 21-10	-0.0977	-0.0957	-0.0890	-0.0833	-0.0962
241	QT 22-10	-0.0449	NA	-0.0401	-0.0377	-0.0442
242	QT 22-21	0.0143	0.0145	0.0179	0.0145	0.0140
243	QT 23-15	-0.0284	-0.0285	-0.0340	-0.0283	-0.0280
244	QT 24-22	-0.0299	-0.0308	-0.0364	-0.0361	-0.0303
245	QT 24-23	-0.0123	-0.0124	-0.0167	-0.0124	-0.0119
246	QT 25-24	-0.0200	NA	-0.0334	-0.0531	-0.0199
247	QT 26-25	-0.0230	NA	-0.0164	0.0040	-0.0222
248	QT 27-25	0.0042	NA	0.0101	0.0441	0.0038
249	QT 27-28	-0.0375	-0.0379	-0.0340	-0.0315	-0.0382
250	QT 29-27	-0.0151	NA	-0.0126	-0.0150	-0.0159
251	QT 30-27	-0.0136	NA	-0.0125	-0.0136	-0.0141
252	QT 30-29	-0.0054	-0.0054	-0.0063	-0.0054	-0.0054
253	QT 28-8	-0.0380	-0.0395	-0.0381	-0.0479	-0.0390
254	QT 28-6	-0.0123	N/A	-0.0143	-0.0450	-0.0146

B.2.6. Multiple Interacting Bad-Data

Table A.6 IEEE 30 Bus System – Multiple Interacting Bad-Data

IEEE 30 bus system - Multiple Interacting Bad-Data at QF 6-9, QG 24, Vm 12						
Sr	Type	Actual	Measurement	Estimated		

				WLS	WLAV	LMR
1	Vm-1	1.0600	1.0600	1.0600	1.0600	1.0605
2	Vm-2	1.0450	NA	1.0413	1.0450	1.0452
3	Vm-3	1.0212	1.0217	1.0217	1.0217	1.0217
4	Vm-4	1.0123	1.0133	1.0131	1.0128	1.0128
5	Vm-5	1.0100	1.0176	1.0298	1.0149	1.0108
6	Vm-6	1.0106	NA	1.0163	1.0114	1.0112
7	Vm-7	1.0026	NA	1.0160	1.0049	1.0032
8	Vm-8	1.0100	1.0010	1.0152	1.0108	1.0107
9	Vm-9	1.0511	NA	1.0547	1.0527	1.0516
10	Vm-10	1.0454	1.0491	1.0483	1.0479	1.0459
11	Vm-11	1.0820	NA	1.0845	1.0826	1.0817
12	Vm-12	1.0573	1.0557	1.0534	1.0571	1.0574
13	Vm-13	1.0710	NA	1.0670	1.0706	1.0709
14	Vm-14	1.0425	NA	1.0396	1.0428	1.0427
15	Vm-15	1.0379	NA	1.0359	1.0387	1.0382
16	Vm-16	1.0446	NA	1.0434	1.0458	1.0448
17	Vm-17	1.0402	NA	1.0427	1.0426	1.0406
18	Vm-18	1.0284	1.0294	1.0283	1.0294	1.0288
19	Vm-19	1.0259	NA	1.0265	1.0270	1.0263
20	Vm-20	1.0300	NA	1.0309	1.0312	1.0304
21	Vm-21	1.0330	1.0431	1.0361	1.0363	1.0336
22	Vm-22	1.0335	NA	1.0366	1.0370	1.0341
23	Vm-23	1.0274	NA	1.0275	1.0307	1.0278
24	Vm-24	1.0218	1.0252	1.0233	1.0252	1.0224
25	Vm-25	1.0176	1.0098	1.0157	1.0098	1.0180
26	Vm-26	0.9999	1.0022	1.0011	1.0022	1.0007
27	Vm-27	1.0235	NA	1.0230	1.0226	1.0238
28	Vm-28	1.0071	1.0052	1.0087	1.0052	1.0077
29	Vm-29	1.0037	1.0042	1.0040	1.0042	1.0037
30	Vm-30	0.9922	NA	0.9922	0.9922	0.9922
31	PG-1	2.6096	2.6103	2.6092	2.6096	2.6097
32	PG-2	0.1830	0.1822	0.1776	0.1822	0.1819
33	PG-3	-0.0240	NA	-0.0243	-0.0236	-0.0243
34	PG-4	-0.0760	-0.0751	-0.0711	-0.0751	-0.0744
35	PG-5	-0.9420	-0.9366	-0.9305	-0.9366	-0.9369
36	PG-6	0.0000	NA	-0.0044	-0.0073	-0.0055
37	PG-7	-0.2280	-0.2306	-0.2328	-0.2306	-0.2310
38	PG-8	-0.3000	NA	-0.2956	-0.2959	-0.2966
39	PG-9	0.0000	NA	0.0000	0.0000	0.0006
40	PG-10	-0.0580	-0.0571	-0.0568	-0.0571	-0.0577
41	PG-11	0.0000	NA	0.0000	0.0000	0.0000
42	PG-12	-0.1120	NA	-0.1242	-0.1177	-0.1175
43	PG-13	0.0000	NA	0.0000	0.0000	0.0000
44	PG-14	-0.0620	-0.0613	-0.0621	-0.0613	-0.0619
45	PG-15	-0.0820	-0.0813	-0.0809	-0.0813	-0.0809
46	PG-16	-0.0350	-0.0349	-0.0366	-0.0349	-0.0354
47	PG-17	-0.0900	NA	-0.0857	-0.0889	-0.0896
48	PG-18	-0.0320	-0.0322	-0.0312	-0.0322	-0.0317
49	PG-19	-0.0950	-0.0944	-0.0945	-0.0944	-0.0949
50	PG-20	-0.0220	NA	-0.0228	-0.0224	-0.0221
51	PG-21	-0.1750	-0.1780	-0.1768	-0.1777	-0.1772

52	PG-22	0.0000	NA	0.0033	-0.0005	0.0004
53	PG-23	-0.0320	NA	-0.0310	-0.0312	-0.0327
54	PG-24	-0.0870	-0.0856	-0.0851	-0.0856	-0.0861
55	PG-25	0.0000	NA	-0.0041	-0.0014	-0.0009
56	PG-26	-0.0350	NA	-0.0341	-0.0354	-0.0347
57	PG-27	0.0000	NA	0.0003	0.0012	-0.0027
58	PG-28	0.0000	NA	0.0004	0.0030	0.0076
59	PG-29	-0.0240	-0.0236	-0.0239	-0.0236	-0.0241
60	PG-30	-0.1060	-0.1057	-0.1063	-0.1057	-0.1062
61	QG-1	-0.2042	-0.2064	-0.1422	-0.2073	-0.1975
62	QG-2	0.4337	-0.4435	0.1676	0.4016	0.4185
63	QG-3	-0.0120	NA	-0.0144	-0.0090	-0.0104
64	QG-4	-0.0160	-0.0154	-0.0833	-0.0154	-0.0148
65	QG-5	0.1666	0.1659	0.3405	0.2117	0.1697
66	QG-6	0.0000	NA	0.1772	0.0280	0.0046
67	QG-7	-0.1090	-0.1109	-0.0679	-0.1109	-0.1097
68	QG-8	0.0611	NA	0.0675	0.0765	0.0640
69	QG-9	0.0000	NA	-0.0003	0.0000	0.0025
70	QG-10	-0.0200	-0.0207	-0.0219	-0.0207	-0.0201
71	QG-11	0.1606	NA	0.1556	0.1559	0.1565
72	QG-12	-0.0750	NA	-0.1225	-0.0933	-0.0771
73	QG-13	0.1045	NA	0.1036	0.1036	0.1031
74	QG-14	-0.0160	-0.0163	-0.0150	-0.0163	-0.0158
75	QG-15	-0.0250	-0.0255	-0.0266	-0.0283	-0.0250
76	QG-16	-0.0180	-0.0180	-0.0248	-0.0180	-0.0185
77	QG-17	-0.0580	NA	-0.0432	-0.0519	-0.0581
78	QG-18	-0.0090	-0.0087	-0.0063	-0.0087	-0.0083
79	QG-19	-0.0340	-0.0348	-0.0330	-0.0348	-0.0343
80	QG-20	-0.0070	NA	-0.0122	-0.0122	-0.0075
81	QG-21	-0.1120	-0.1106	-0.1095	-0.1106	-0.1101
82	QG-22	0.0000	NA	0.0084	0.0182	0.0008
83	QG-23	-0.0160	NA	-0.0111	-0.0041	-0.0160
84	QG-24	-0.0670	-0.0666	-0.0615	-0.0342	-0.0670
85	QG-25	0.0000	NA	-0.0227	-0.0935	-0.0004
86	QG-26	-0.0230	NA	-0.0157	0.0040	-0.0222
87	QG-27	0.0000	NA	-0.0025	0.0311	0.0001
88	QG-28	0.0000	NA	-0.0811	-0.0620	-0.0015
89	QG-29	-0.0090	NA	-0.0061	-0.0043	-0.0095
90	QG-30	-0.0190	-0.0190	-0.0188	-0.0190	-0.0195
91	PF 1-2	1.7331	NA	1.7327	1.7331	1.7326
92	PF 1-3	0.8765	0.8707	0.8765	0.8765	0.8771
93	PF 2-4	0.4365	0.4395	0.4326	0.4361	0.4369
94	PF 3-4	0.8214	NA	0.8211	0.8218	0.8217
95	PF 2-5	0.8236	0.8199	0.8260	0.8236	0.8217
96	PF 2-6	0.6038	NA	0.6001	0.6034	0.6039
97	PF 4-6	0.7213	0.7291	0.7214	0.7215	0.7205
98	PF 5-7	-0.1478	-0.1474	-0.1344	-0.1423	-0.1445
99	PF 6-7	0.3813	0.3870	0.3734	0.3785	0.3810
100	PF 6-8	0.2956	0.2917	0.2925	0.2917	0.2918
101	PF 6-9	0.2772	0.2717	0.2793	0.2796	0.2786
102	PF 6-10	0.1584	0.1596	0.1596	0.1598	0.1593
103	PF 9-11	0.0000	NA	0.0000	0.0000	0.0000

104	PF 9-10	0.2772	NA	0.2793	0.2796	0.2792
105	PF 4-12	0.4419	NA	0.4427	0.4426	0.4449
106	PF 12-13	0.0000	NA	0.0000	0.0000	0.0000
107	PF 12-14	0.0786	0.0800	0.0766	0.0773	0.0781
108	PF 12-15	0.1789	NA	0.1730	0.1767	0.1775
109	PF 12-16	0.0724	0.0727	0.0689	0.0710	0.0717
110	PF 14-15	0.0158	0.0156	0.0138	0.0152	0.0155
111	PF 16-17	0.0369	NA	0.0319	0.0356	0.0358
112	PF 15-18	0.0602	0.0593	0.0570	0.0593	0.0595
113	PF 18-19	0.0278	0.0281	0.0255	0.0268	0.0275
114	PF 19-20	-0.0673	NA	-0.0691	-0.0676	-0.0675
115	PF 10-20	0.0903	NA	0.0929	0.0911	0.0905
116	PF 10-17	0.0533	0.0536	0.0540	0.0536	0.0541
117	PF 10-21	0.1579	NA	0.1587	0.1604	0.1594
118	PF 10-22	0.0762	NA	0.0765	0.0773	0.0769
119	PF 21-22	-0.0183	NA	-0.0191	-0.0184	-0.0189
120	PF 15-23	0.0504	NA	0.0469	0.0492	0.0505
121	PF 22-24	0.0574	0.0580	0.0601	0.0580	0.0578
122	PF 23-24	0.0180	0.0179	0.0157	0.0177	0.0175
123	PF 24-25	-0.0121	-0.0118	-0.0099	-0.0104	-0.0113
124	PF 25-26	0.0354	0.0357	0.0345	0.0357	0.0352
125	PF 25-27	-0.0476	-0.0480	-0.0486	-0.0480	-0.0475
126	PF 28-27	0.1807	0.1793	0.1816	0.1793	0.1837
127	PF 27-29	0.0619	NA	0.0620	0.0615	0.0621
128	PF 27-30	0.0709	0.0722	0.0710	0.0706	0.0711
129	PF 29-30	0.0370	0.0371	0.0372	0.0371	0.0371
130	PF 8-28	-0.0054	NA	-0.0042	-0.0053	-0.0059
131	PF 6-28	0.1867	NA	0.1861	0.1823	0.1825
132	PT 2-1	-1.6809	-1.6536	-1.6810	-1.6809	-1.6806
133	PT 3-1	-0.8454	NA	-0.8454	-0.8454	-0.8460
134	PT 4-2	-0.4263	NA	-0.4227	-0.4260	-0.4267
135	PT 4-3	-0.8129	-0.8014	-0.8125	-0.8133	-0.8131
136	PT 5-2	-0.7942	NA	-0.7961	-0.7943	-0.7924
137	PT 6-2	-0.5843	-0.5796	-0.5808	-0.5840	-0.5845
138	PT 6-4	-0.7150	NA	-0.7145	-0.7152	-0.7142
139	PT 7-5	0.1495	NA	0.1366	0.1441	0.1461
140	PT 7-6	-0.3775	NA	-0.3694	-0.3747	-0.3772
141	PT 8-6	-0.2946	NA	-0.2915	-0.2906	-0.2907
142	PT 9-6	-0.2772	NA	-0.2793	-0.2796	-0.2786
143	PT 10-6	-0.1584	NA	-0.1596	-0.1598	-0.1593
144	PT 11-9	0.0000	NA	0.0000	0.0000	0.0000
145	PT 10-9	-0.2772	-0.2796	-0.2793	-0.2796	-0.2792
146	PT 12-4	-0.4419	-0.4497	-0.4427	-0.4426	-0.4449
147	PT 13-12	0.0000	NA	0.0000	0.0000	0.0000
148	PT 14-12	-0.0778	NA	-0.0759	-0.0766	-0.0774
149	PT 15-12	-0.1767	-0.1733	-0.1710	-0.1746	-0.1754
150	PT 16-12	-0.0719	NA	-0.0685	-0.0705	-0.0712
151	PT 15-14	-0.0158	NA	-0.0138	-0.0152	-0.0155
152	PT 17-16	-0.0368	NA	-0.0319	-0.0355	-0.0357
153	PT 18-15	-0.0598	NA	-0.0567	-0.0589	-0.0591
154	PT 19-18	-0.0277	NA	-0.0255	-0.0267	-0.0274
155	PT 20-19	0.0674	0.0687	0.0693	0.0678	0.0677

156	PT 20-10	-0.0894	-0.0902	-0.0920	-0.0902	-0.0897
157	PT 17-10	-0.0532	NA	-0.0539	-0.0534	-0.0539
158	PT 21-10	-0.1567	-0.1564	-0.1576	-0.1593	-0.1583
159	PT 22-10	-0.0757	NA	-0.0759	-0.0768	-0.0763
160	PT 22-21	0.0183	0.0184	0.0192	0.0184	0.0189
161	PT 23-15	-0.0500	-0.0507	-0.0466	-0.0489	-0.0502
162	PT 24-22	-0.0569	-0.0568	-0.0595	-0.0575	-0.0573
163	PT 24-23	-0.0180	-0.0177	-0.0156	-0.0177	-0.0175
164	PT 25-24	0.0122	NA	0.0101	0.0110	0.0114
165	PT 26-25	-0.0350	NA	-0.0341	-0.0354	-0.0347
166	PT 27-25	0.0479	NA	0.0489	0.0484	0.0478
167	PT 27-28	-0.1807	-0.1842	-0.1816	-0.1793	-0.1837
168	PT 29-27	-0.0610	NA	-0.0611	-0.0607	-0.0612
169	PT 30-27	-0.0693	NA	-0.0694	-0.0690	-0.0695
170	PT 30-29	-0.0367	-0.0367	-0.0369	-0.0367	-0.0368
171	PT 28-8	0.0055	0.0054	0.0042	0.0054	0.0059
172	PT 28-6	-0.1862	NA	-0.1854	-0.1817	-0.1820
173	QF 1-2	-0.2470	NA	-0.1814	-0.2470	-0.2402
174	QF 1-3	0.0428	0.0421	0.0392	0.0397	0.0427
175	QF 2-4	0.0475	0.0481	0.0219	0.0446	0.0454
176	QF 3-4	-0.0385	NA	-0.0444	-0.0386	-0.0371
177	QF 2-5	0.0278	-0.0268	-0.0927	0.0027	0.0245
178	QF 2-6	0.0137	NA	-0.0395	0.0096	0.0112
179	QF 4-6	-0.1591	-0.1583	-0.2777	-0.1648	-0.1611
180	QF 5-7	0.1149	0.1149	0.1670	0.1354	0.1155
181	QF 6-7	-0.0278	-0.0284	-0.1205	-0.0463	-0.0278
182	QF 6-8	-0.0720	-0.0736	-0.0607	-0.0736	-0.0741
183	QF 6-9	-0.0809	-0.0822	-0.0702	-0.0849	-0.0802
184	QF 6-10	0.0019	NA	0.0074	-0.0013	0.0021
185	QF 9-11	-0.1560	-0.1516	-0.1513	-0.1516	-0.1521
186	QF 9-10	0.0588	NA	0.0649	0.0500	0.0581
187	QF 4-12	0.1441	NA	0.1646	0.1476	0.1466
188	QF 12-13	-0.1032	-0.1023	-0.1023	-0.1023	-0.1018
189	QF 12-14	0.0240	0.0237	0.0205	0.0223	0.0237
190	QF 12-15	0.0679	NA	0.0548	0.0604	0.0669
191	QF 12-16	0.0335	0.0335	0.0207	0.0267	0.0330
192	QF 14-15	0.0065	0.0063	0.0040	0.0045	0.0064
193	QF 16-17	0.0144	NA	-0.0051	0.0076	0.0134
194	QF 15-18	0.0160	0.0153	0.0084	0.0154	0.0155
195	QF 18-19	0.0062	0.0059	0.0015	0.0059	0.0064
196	QF 19-20	-0.0279	NA	-0.0316	-0.0290	-0.0280
197	QF 10-20	0.0371	NA	0.0463	0.0435	0.0376
198	QF 10-17	0.0443	0.0449	0.0488	0.0449	0.0454
199	QF 10-21	0.1001	NA	0.0980	0.0886	0.0985
200	QF 10-22	0.0460	NA	0.0450	0.0387	0.0453
201	QF 21-22	-0.0143	NA	-0.0139	-0.0243	-0.0140
202	QF 15-23	0.0291	NA	0.0199	0.0171	0.0286
203	QF 22-24	0.0306	0.0295	0.0385	0.0315	0.0310
204	QF 23-24	0.0124	0.0125	0.0083	0.0125	0.0120
205	QF 24-25	0.0201	0.0196	0.0294	0.0541	0.0201
206	QF 25-26	0.0237	0.0233	0.0162	-0.0035	0.0228
207	QF 25-27	-0.0037	-0.0038	-0.0098	-0.0367	-0.0033

208	QF 28-27	0.0504	0.0519	0.0562	0.0475	0.0514
209	QF 27-29	0.0167	NA	0.0145	0.0133	0.0173
210	QF 27-30	0.0166	0.0173	0.0157	0.0153	0.0171
211	QF 29-30	0.0061	0.0060	0.0068	0.0074	0.0061
212	QF 8-28	-0.0054	NA	0.0124	0.0084	-0.0046
213	QF 6-27	0.0011	NA	0.0703	0.0467	0.0026
214	QT 2-1	0.3447	0.3363	0.2779	0.3447	0.3374
215	QT 3-1	0.0265	NA	0.0301	0.0296	0.0267
216	QT 4-2	-0.0554	NA	-0.0304	-0.0527	-0.0533
217	QT 4-3	0.0544	0.0525	0.0603	0.0545	0.0530
218	QT 5-2	0.0517	NA	0.1735	0.0763	0.0542
219	QT 6-2	0.0058	0.0060	0.0585	0.0098	0.0083
220	QT 6-4	0.1719	NA	0.2925	0.1777	0.1738
221	QT 7-5	-0.1313	NA	-0.1829	-0.1515	-0.1320
222	QT 7-6	0.0223	NA	0.1150	0.0407	0.0222
223	QT 8-6	0.0666	NA	0.0550	0.0681	0.0686
224	QT 9-6	0.0972	NA	0.0862	0.1015	0.0965
225	QT 10-6	0.0110	NA	0.0055	0.0143	0.0109
226	QT 11-9	0.1606	NA	0.1556	0.1559	0.1565
227	QT 10-9	-0.0508	-0.0521	-0.0568	-0.0420	-0.0500
228	QT 12-4	-0.0972	-0.1004	-0.1163	-0.1004	-0.0990
229	QT 13-12	0.1045	NA	0.1036	0.1036	0.1031
230	QT 14-12	-0.0225	NA	-0.0190	-0.0208	-0.0222
231	QT 15-12	-0.0636	-0.0629	-0.0510	-0.0563	-0.0627
232	QT 16-12	-0.0324	NA	-0.0198	-0.0257	-0.0319
233	QT 15-14	-0.0064	NA	-0.0040	-0.0045	-0.0063
234	QT 17-16	-0.0141	NA	0.0052	-0.0074	-0.0131
235	QT 18-15	-0.0152	NA	-0.0077	-0.0147	-0.0147
236	QT 19-18	-0.0061	NA	-0.0014	-0.0058	-0.0063
237	QT 20-19	0.0283	0.0282	0.0320	0.0293	0.0283
238	QT 20-10	-0.0353	-0.0363	-0.0442	-0.0415	-0.0358
239	QT 17-10	-0.0439	NA	-0.0484	-0.0445	-0.0450
240	QT 21-10	-0.0977	-0.0957	-0.0956	-0.0863	-0.0961
241	QT 22-10	-0.0449	NA	-0.0439	-0.0377	-0.0442
242	QT 22-21	0.0143	0.0145	0.0139	0.0243	0.0140
243	QT 23-15	-0.0284	-0.0285	-0.0194	-0.0166	-0.0280
244	QT 24-22	-0.0299	-0.0308	-0.0376	-0.0308	-0.0303
245	QT 24-23	-0.0123	-0.0124	-0.0082	-0.0124	-0.0119
246	QT 25-24	-0.0200	NA	-0.0291	-0.0532	-0.0199
247	QT 26-25	-0.0230	NA	-0.0157	0.0040	-0.0222
248	QT 27-25	0.0042	NA	0.0103	0.0375	0.0038
249	QT 27-28	-0.0375	-0.0379	-0.0430	-0.0349	-0.0381
250	QT 29-27	-0.0151	NA	-0.0129	-0.0117	-0.0156
251	QT 30-27	-0.0136	NA	-0.0127	-0.0123	-0.0140
252	QT 30-29	-0.0054	-0.0054	-0.0062	-0.0067	-0.0055
253	QT 28-8	-0.0380	-0.0395	-0.0560	-0.0517	-0.0390
254	QT 28-6	-0.0123	N/A	-0.0813	-0.0578	-0.0139

B.3. IEEE 118 Bus System

B.3.1. White Noise

The results are available in attached CD.

B.3.2. Single Bad-Data as Power Flow Meter

The results are available in attached CD.

B.3.3. Single Bad-Data as Power Injection Meter

The results are available in attached CD.

B.3.4. Single Bad-Data as Voltage Magnitude Meter

The results are available in attached CD.

B.3.5. Multiple Non-Interacting Bad-Data

The results are available in attached CD.

B.3.6. Multiple Interacting Bad-Data

The results are available in attached CD.

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